University of Southampton

Faculty of Environmental and Life Sciences

School of Ocean and Earth Science

Assessing the Impacts of Commercial Gas Hydrate Development

by David Christopher Riley

ORCID ID 0000-0001-9829-004X

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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Gas hydrate offers a large prospective reserve of unconventional natural gas. While research continues into possible production technology, investigation of the broader impacts of commercial development is needed to determine its future. I present the first attempt to comparatively analyse different commercial gas hydrate projects considering economic, social and environmental impacts, providing a foundation framework for future study.

To this end, I develop a protocol using the ELECTRE multi-criteria decision analysis method for assessing between different gas hydrate exploitation projects. I define possible economic, social and environmental impacts to measure within this protocol, and suggest how each can be appraised by quantitative or qualitative decision criteria. These criteria are used, in collaboration with stakeholders, for structured comparative evaluation of development alternatives by means of an impact matrix. I construct criteria weights and decision thresholds from stakeholder input and use this information to calculate alternative rankings.

Uncertainty remains in the effect of heterogeneity in petrophysical parameters on gas production, and this uncertainty is currently poorly represented in many production models. Gas hydrate saturation heterogeneity has been seen in natural systems, but it has not been modelled adequately for my protocol needs. I use TOUGH+Hydrate, a numerical thermo-hydraulic code for gas hydrate bearing geological systems, to provide a detailed quantification of gas production error margins resulting from heterogeneity in gas hydrate saturation. This modelling indicates that 10% saturation heterogeneity causes gas production fluctuations of ±25%, and 1% saturation variation in heterogeneous systems has equivalent impact to 10% saturation variation in homogeneous systems.

I test the complete protocol in Alaska to explore wider public perception of gas hydrate development, where I find society split into two groups, those prioritising resource production and economic returns from development, and those prioritising maximum benefit, or minimum damage, in the affected social and environmental systems. During fieldwork, the protocol proved accessible to a wide range of stakeholders across Alaskan society, satisfying the need for a broadly applicable tool. In all cases, Alaskan gas hydrate development is unsupported under current conditions due to the high economic, social and environmental costs of necessary infrastructure.

Lastly I give examples of three further sites where the protocol may see use to illustrate the range of problems it has been designed for. For each site I suggest a series of qualitative and quantitative impact measures that may be used in future work and highlight a range of operational issues to consider. I use scenario analysis to explore the impact of varying the input parameters and ensure the protocol computes rational and justifiable results. Future protocol applications will benefit from wider collaboration throughout for better understanding of stakeholder priorities, especially with traditionally under-represented groups. Each of these case studies allows ultimate protocol refinement into a powerful and versatile tool, suitable for evaluating any gas hydrate production proposal. These studies show how an MCDA approach can be applied to gas hydrate development, providing a framework for future impact analysis.

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Research Thesis: Declaration of Authorship

Print name: **David Riley**

Title of thesis: **Assessing the Impacts of Commercial Gas Hydrate Development**

I, David Christopher Riley, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Riley, D., Marin-Moreno, H., Minshull, T.A., 2019. The effect of heterogeneities in hydrate saturation on gas production from natural systems. Journal of Petroleum Science and Engineering 183. https://doi.org/10.1016/j.petrol.2019.106452

Riley, D., Schaafsma, M., Marin-Moreno, H., Minshull, T.A., 2020. A social, environmental and economic evaluation protocol for potential gas hydrate exploitation projects. Applied Energy 263, 114651. https://doi.org/10.1016/j.apenergy.2020.114651

8. Work directly related to this thesis has been presented at the following conferences:

Riley, D., Marin-Moreno, H., Minshull, T.A., Schaafsma, M., 2018. A multi-criteria approach to social, economic and environmental assessment of gas hydrate development projects, in: Gas Hydrates: A Major Unconventional Energy Resource - When Will They Be Produced? Presented at the AGU 2018, Washington, D.C.

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Riley, D., Schaafsma, M., Marin-Moreno, H., Minshull, T.A., 2017. Assessing the Viability of Arctic Gas Hydrate Exploitation. Presented at the British Geophysical Association Postgraduate Research in Progress Conference, University of Aberdeen.

Riley, D., Schaafsma, M., Marin-Moreno, H., Minshull, T.A., 2017. The Potential Socio-economic Impacts of Arctic Gas Hydrate Exploitation, in: Geology and Societal Change: What Difference Does Your Research Make? Presented at the Geologists Association Student Symposium, Burlington House, London.

Riley, D., Schaafsma, M., Marin-Moreno, H., Minshull, T., 2017. The Potential Socio-economic Impacts of Gas Hydrate Exploitation, in: Unconventional Hydrocarbon Resources: Advances and New Technologies. Presented at the EGU 2017, Geophysical Research Abstracts, Vienna, Austria.

Signature: Date:

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I began this work in 2016 with very little experience of gas hydrate or social sciences research. I end here in 2020 having studied and discussed gas hydrate across the globe, with a passionate interest for integrating social science insight into ongoing debate surrounding their development. I greatly appreciate my supervisors for having faith in me, and their contributions to the resulting work; Dr Héctor Marín Moreno for his bottomless enthusiasm, problem solving and continued motivation; Dr Marije Schaafsma for her patience and willingness to broaden my horizons; and Professor Tim Minshull for his steady hand guiding the project. Thanks also to the Leverhulme Trust and NOCS for the funding that made this study and especially the fieldwork, possible.

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Definitions and Abbreviations

AHP	Analytical Hierarchy Process
AIST	Advanced Industrial Science and Technology
ANCSA	Alaska Native Claims Settlement Act
ANP	Analytical Network Process
ANWR	Arctic National Wildlife Refuge
BSR	Bottom Simulating Reflector
CBA	Cost-Benefit Analysis
COPRAS	Complex Proportional Assessment
DPSIR	Drivers-Pressure-State-Impacts-Response
DPSWR	Drivers-Pressure-State-Welfare-Response
E-SHRIMP	Environmental, Social and Health Risk and Impact Management Process
EEZ	Exclusive Economic Zone
ELECTRE	Elimination Et Choix Traduisant la Realité
ESIA	Environmental and Social Impact Assessment
EU	European Union
FPIC	Free, Prior and Informed Consent
FPSO	Floating Production Storage and Offloading
GHG	Greenhouse Gas
HHI	Herfindahl-Hirschman Index
IUCN	International Union for Conservation of Nature
JOGMEC	Japanese Oil, Gas and Metals National Corporation
LCOE	Levelised Cost of Energy

LNG	Liquefied Natural Gas
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MCDA	Multi-Criteria Decision Analysis
METI	Ministry of Economy, Trade and Industry
NGO	Non-Governmental Organisation
NPV	Net Present Value
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
REES	Risky External Energy Supply
SMART	Simple Multi-Attribute Rating Technique
TAPS	Trans-Alaska Pipeline System
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WWF	World Wide Fund for Nature
YNAO	Yamalo-Nenets Autonomous Okrug

Chapter 1 Introduction

1.1 Positioning of Thesis

1.1.1 Global Energy Systems and Gas Hydrate

Global energy supply and demand is in a state of constant evolution. Global demand is forecast to grow through 2050, with natural gas projected to provide an increasing share of primary energy (Frei et al., 2013; IEA, 2017). As such, in recent years, development of unconventional energy resources such as shale gas has increased (Chong et al., 2016). There are also geopolitical motivations for pursuing these resources, as governments seek domestic resources for energy security, to avoid reliance on import supply chains that may be disrupted (Wang and Krupnick, 2015). Each new resource that is developed brings specific consequences, and so must be managed appropriately. The past few decades have seen increased importance placed on understanding the social and environmental impacts of any project, to a new paradigm where justification for resource exploitation moves beyond solely pursuing financial gains (Jenkins et al., 2016). Projects are considered by their total social benefit to impact communities, or their environmental cost, with legislation at national and international level stressing the need to understand the relationship between any resource development and the affected environment (Glasson and Therivel, 2013). Greater emphasis is placed on understanding inequities in impact distribution when a new resource is considered, with other concerns such as reliability and accessibility placed level with affordability (Jenkins et al., 2016; Kumar et al., 2017). Currently, concerns surrounding climate change motivate more investigation of the impacts of developing energy sources on the natural environment (Chong et al., 2016). This atmosphere promotes natural gas use, as natural gas generates less greenhouse gas emissions per unit energy than coal or oil, making it a cleaner alternative than other fossil fuels (Burnham et al., 2012). New technology and media have given environmental advocacy groups a co-ordinated platform with greater influence, necessitating more environmentally conscientious development design (Hall et al., 2015; Williams et al., 2017). Overall, public opinion towards development of further unconventional resources is divided and complex (Ceccoli, 2018).

Gas hydrate is a natural gas compound where molecules of natural gas, usually methane, are contained within an ice lattice (Sloan and Koh, 2007). Gas hydrate is a potential unconventional source of natural gas, as the contained gas can be liberated by changing the formation conditions to induce gas hydrate dissociation (Chong et al., 2016). Gas hydrate is only stable in a narrow window of high pressure, low temperature conditions, found offshore at shallow depth beneath the seafloor at continental slopes or onshore beneath permafrost in polar regions (Boswell and Collett, 2011). Despite the specific conditions required for gas hydrate in nature, vast amounts of natural gas are thought to be stored in gas hydrate worldwide (Figure 1.1; Boswell and Collett, 2011). Gas hydrate has been found as a result of drilling and seismic exploration, and more gas hydrate may exist in less investigated areas (Sloan and Koh, 2007). Scientific tests have taken place in Alaska (Hunter et al., 2011), Canada (Ashford et al., 2012b), the South China Sea (Li et al., 2018) and offshore Japan (Konno et al., 2017) supported by research laboratories, the petroleum industry and national governments (Figure 1.2). These tests aim to refine gas hydrate exploitation, and understand the consequences of liberating natural gas from gas hydrate. Gas hydrate production has been investigated for decades, but recent projects have made commercial development closer to a technical reality (Max and Johnson, 2016). Although gas hydrate is not the primary commercial target in any current producing field, gas hydrate-derived gas is suggested as a possible contributor to total gas production in some Russian and Alaskan fields (Makogon and Omelchenko, 2013; Walsh et al., 2008).

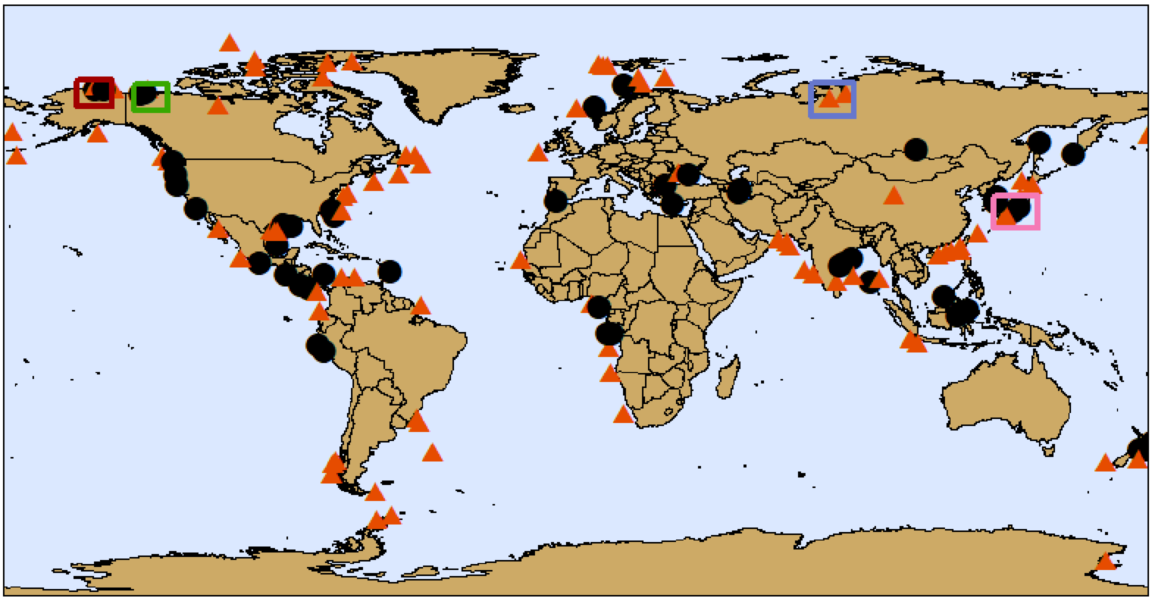

Figure 1.1 *Global map of locations where gas hydrate is known (black circles) or believed (orange triangles) to occur (Ruppel, 2018). Coloured areas are sites used as case studies in Chapters 4 and 5; the Alaska North Slope (red; Section 4.4), Canada's Mackenzie Delta (green; Section 5.2), the Messoyakha field in Siberia (blue; Section 5.3) and the Nankai Trough, offshore Japan (pink; Section 5.4).*

1.1.2 Gas Hydrate Production and Modelling Efforts

Different mechanisms proposed for commercial gas production from gas hydrate include depressurisation, thermal stimulation, use of an inhibitor, or CO_2 exchange (Figure 1.3, Chong et al., 2016). Depressurisation lowers the pressure of the gas hydrate bearing layer below gas hydrate stability by fluid removal from surrounding layers, or the gas hydrate bearing layer itself. Compared to conventional resources, the production of gas hydrate co-produces much higher volumes of water, requiring additional pumping capacity to maintain low pressures and consistent gas flow (Moridis et al., 2011a). Thermal stimulation introduces heat to the gas hydrate reservoir by injection of a hot fluid, raising formation temperature above gas hydrate stability conditions (Figure 1.3, Demirbas, 2010). Much energy is wasted in thermal stimulation heating material surrounding the gas hydrate bearing layers, reducing efficiency of the process (Demirbas, 2010). Rather than causing dissociation alone, thermal stimulation is seen as most viable when applied with depressurisation to increase productivity. In either case, the self-preservation behaviour of gas hydrate, where the nature of dissociation acts to try to return formation conditions to the gas hydrate stability field, necessitates constant energy input to maintain suitable pressure and temperature conditions for gas production (Chong et al., 2016). Inhibitors are used in commercial gas production to prevent the formation of solid gas hydrate in pipelines, as a mechanism for flow assurance (Sloan et al., 2010). Inhibitors act by altering the position of the gas hydrate stability curve (Figure 1.3; Sloan and Koh, 2007). Similar inhibitors can be injected from wells to dissociate gas hydrate, although the cost is high and the process is only viable in certain high porosity/permeability reservoirs (Demirbas, 2010). Finally, CO_2 exchange is a theoretically viable gas hydrate production mechanism, as injected CO_2 could substitute for the methane gas in solid gas hydrate, sequestering CO_2 and producing methane, while retaining gas hydrate in the formation (Koh et al., 2012). This method has been field tested, but has yet to be proven successful on a commercial scale (Boswell et al., 2017b). Depressurisation is seen as the most efficient of all these approaches (Moridis et al., 2011a), and has been used as the production method in test wells in Arctic Canada (Ashford et al., 2012b) and offshore of Japan (Konno et al., 2017) and China (Li et al., 2018).

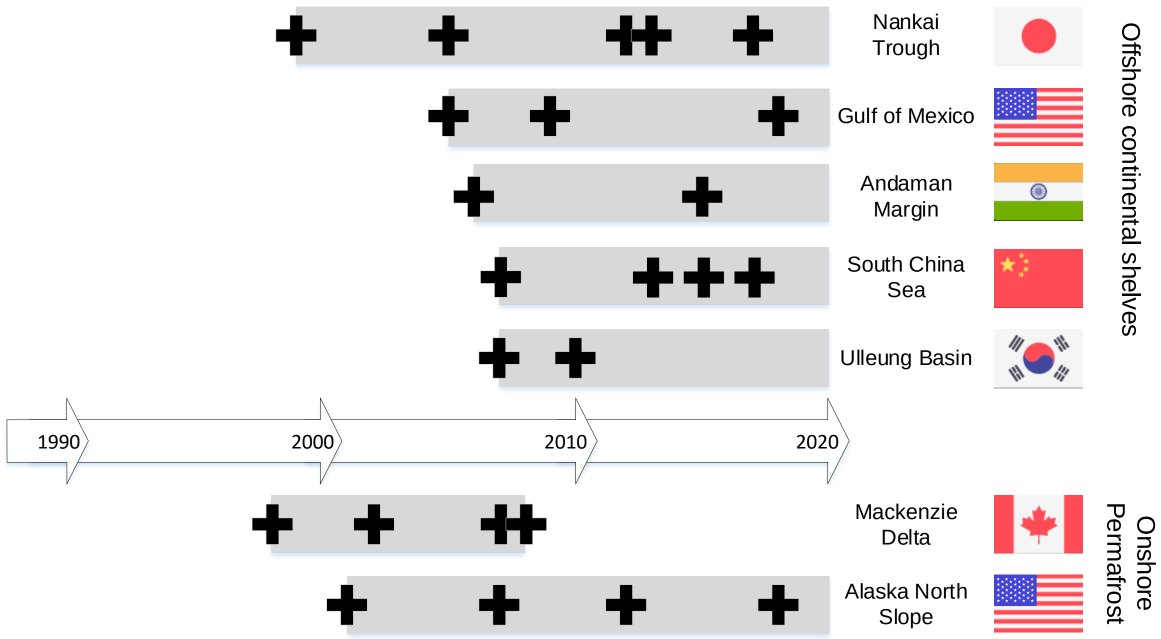

Figure 1.2 *Chronology of major global gas hydrate projects as of late 2019, divided by environment (Ruppel, 2018). Shading shows active years, with crosses corresponding to drilling projects.*

Without any active commercial gas hydrate development, studies attempting to predict the scale of gas hydrate-derived gas production rely on numerical modelling. Although numerical modelling is a common practice when developing any resource, gas hydrate production modelling is less advanced than that of more conventional resources, as gas hydrate models include many uncertainties that affect the reliability of production forecasts, and there is a lack of commercial projects to validate the numerical results (Wilson et al., 2011). Necessary parameters to define a gas hydrate system include permeability, thermal conductivity, gas hydrate saturation, and the local pressure and temperature conditions.

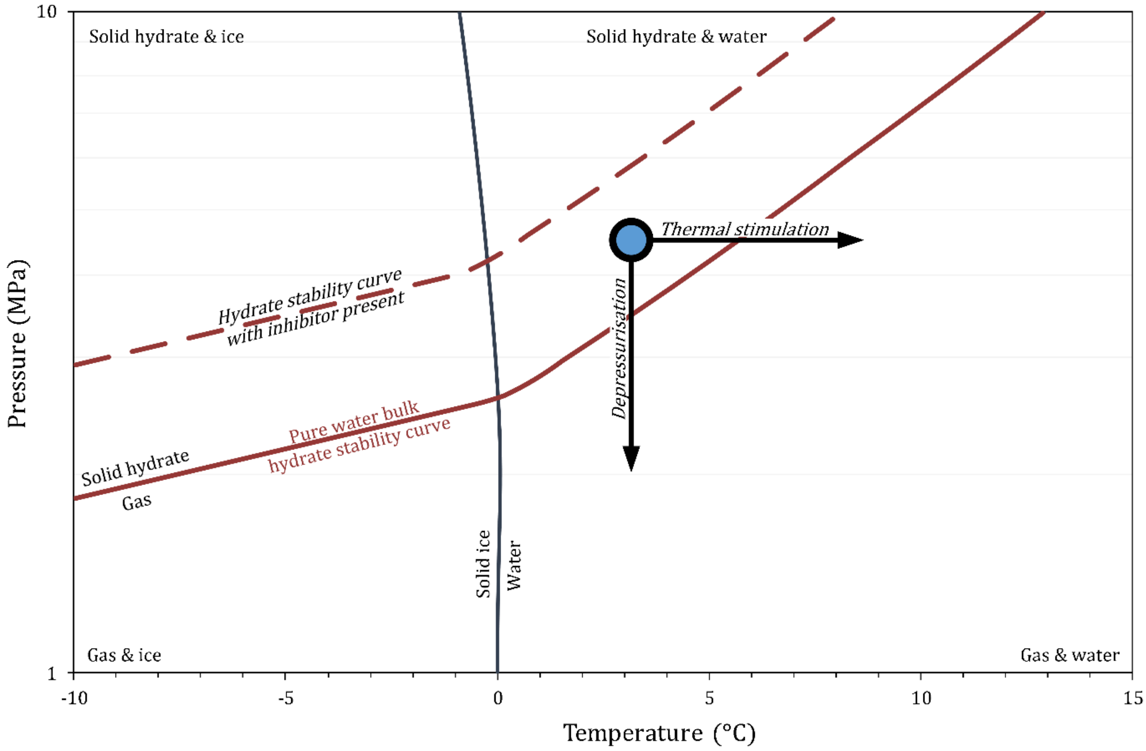

Figure 1.3 *Schematic diagram showing the possible production mechanisms for gas from initially stable solid gas hydrate (blue dot), plotted on the hydrate stability field.*

Gas hydrate systems include liquid and gas phases that interact, leading to two distinct permeabilities; the intrinsic permeability of the material overall; and the relative permeability of each fluid phase in the presence of other phases. As gas hydrate changes phase during dissociation, the permeability of the system changes during production (Bhade and Phirani, 2015). These phase changes also make it difficult to experimentally estimate permeability, even under controlled conditions (Li et al., 2016). Permeability controls the distribution of gas hydrate within the formation, and impacts production by controlling the flow of produced gas to the well, convective flow of heat and the rate of depressurisation front propagation through the formation. Solid gas hydrate can form with different habits, commonly classified as cementing or pore filling (Waite et al., 2009), and pore scale variations that are impossible to precisely quantify in natural systems control how depressurisation propagates through the formation (Kang et al., 2016). Existing modelling software allows permeability to be dependent on gas hydrate saturation, by using an evolving porous medium approach (Moridis, 2008). Acknowledging difficulties in quantifying representative natural permeability values, recent modelling efforts have varied permeability in sensitivity analysis, with a resulting order of magnitude impact on gas production estimates (Ajayi et al., 2018; Chen et al., 2018).

While permeability controls convective transfer during gas hydrate dissociation, thermal conductivity controls heat conduction, with more heat supply causing faster dissociation (Zhao et al., 2014). The endothermic nature of gas hydrate dissociation can cause ice formation, potentially blocking fluid flow pathways and hindering production efforts (B. Wang et al., 2018). In low temperature natural systems, such as those near permafrost, relatively little endothermic dissociation is necessary to lower temperature sufficiently for ice to form (Moridis and Reagan, 2011). In warmer systems, more dissociation can occur before ice can form, allowing a higher production rate (Moridis and Reagan, 2011). Thermal conductivity in gas hydrate generally has also been shown to be temperature dependent (Waite et al., 2007). Sensitivity analysis shows thermal conductivity has a lower impact on gas production than permeability, suggesting convective transfer dominates (Ruan et al., 2012).

Well logging efforts have shown high variations in gas hydrate saturation within single reservoirs, as structural variations alter capillary pressure, causing irregular gas hydrate formation (Behseresht and Bryant, 2012). Higher gas hydrate saturation, although providing more gas in the system, also lowers effective permeability and slows dissociation (Uddin et al., 2014). An irregular gas hydrate saturation therefore causes equally irregular system fluid flow. Recent 2D modelling efforts have represented the gas hydrate domain as a series of layers of different gas hydrate saturation (Ajayi et al., 2018; Jin et al., 2018). Varying the hydrate saturation of these model layers changes the ultimate gas production rate, and time taken to reach maximum production rate (Bhade and Phirani, 2015). 3D heterogeneity in gas hydrate saturation in natural systems is being recognised and incorporated into production models (Myshakin et al., 2016; Uddin et al., 2014), but these simulations only generate a best estimate gas hydrate distribution from available data, without sensitivity analysis. The uncertainty in gas production in a heterogeneous natural system, where gas hydrate saturation at all points cannot be precisely known, is not clearly defined.

Despite the known impacts of heterogeneity, many modelling efforts homogenise the gas hydrate bearing layers into one homogenous domain (e.g. Kim et al., 2018; Yan et al., 2018; Yu et al., 2018; Zheng et al., 2018). A homogenous domain is computationally simpler, and is often used when simulation parameters are derived from a drilled well, as a well provides a spatially limited snapshot of parameters (Anderson et al., 2011). However, initial studies exploring heterogeneity suggest homogenisation may dramatically change production estimates (Reagan et al., 2010), calling into question the reliability of many current models. Downhole logging suggest that saturation could vary at short length scales where gas hydrate is found in a layered sedimentary reservoir (Lee and Collett, 2011), which is considered the dominant site type for possible future production (Boswell and Collett, 2011). Therefore there is evidence that gas hydrate reservoirs have saturation heterogeneities, and that these heterogeneities will impact gas production, but this hypothesis has not been tested and quantified. An accurate production estimate is necessary when evaluating any commercial project, as gas production rate is the primary driving force behind most gas development proposals. Therefore, this thesis quantifies the impact of incorporating uncertainty in the subsurface on gas production estimates from gas hydrate reservoirs.

There are a range of software packages available for numerical modelling, although benchmarking tests suggest each produces similar results (Anderson et al., 2011). I use TOUGH+HYDRATE (Moridis, 2008), one of the leading numerical packages for simulation of gas hydrate bearing geological systems that has been widely used and validated in simulation problems (e.g. Grover et al., 2008; Jin et al., 2018; Moridis et al., 2011a; Reagan et al., 2010). TOUGH+HYDRATE was also chosen for a number of practical reasons: it has been proven to work on the hardware available, individuals with experience using the software were available within the university and relationships existed with the external developers of the software that could prove invaluable for troubleshooting.

1.1.3 Consideration of Gas Hydrate as a Resource

As technology for producing gas from gas hydrate continues to be refined, analysis of the broader impacts of gas hydrate development has lagged behind. This thesis provides the groundwork for more holistic future evaluation of the commercial potential of gas hydrate reservoirs. The impacts from developing conventional sources of natural gas are well-established, and evaluation mechanisms for other unconventional resources are being refined as these resources are developed (Rahm and Riha, 2012). It is accepted that any large resource development project will have a series of economic, social and environmental impacts that must be managed. Environmental impact assessment has been proposed for evaluating gas hydrate production, if modified appropriately (Beaudoin et al., 2014), but this approach only includes environmental impacts. Environmental and social impact assessment (ESIA) is now common in the appraisal of large development projects (Morgan, 2012), but has not been considered with gas hydrate development. ESIA predicts the impacts of development on the natural and human spheres, then proposes how to mitigate or monitor adverse impacts. ESIA focuses on mitigating the adverse impacts of any project (Therivel and Wood, 2017), while we seek a broader comparison of projects' positive and negative impacts. We also seek a more explicit link between the technical specifications of any project and its resulting impacts, where ESIA is usually distinct from resource evaluation. Current energy policy includes the provision that any impact assessment done is participatory and representative (Esteves et al., 2012). But, while this practice is regulated and tailored for specific conventional resources (Barker and Jones, 2013), no protocol structure exists for gas hydrate. Compared to conventional oil and gas development, gas hydrate development is currently surrounded by considerable uncertainty.

For gas hydrate there has been little investigation of the social or environmental impacts that may be associated with commercial production (Li et al., 2016). Environmentally and socially, gas hydrate research has focussed on whether gas hydrate derived gas could contribute to global climate issues (Chong et al., 2016). Gas hydrate is considered a potential atmospheric methane source by the IPCC, although it is difficult to isolate the contribution of gas hydrate to global emissions (Ruppel and Kessler, 2017). This issue is not necessarily linked to gas hydrate commercialisation, as commercial targets are deep, confined reservoirs with high gas hydrate saturation, whereas most climatic concern is related to natural gas hydrate dissociation in shallow, disseminated deposits of no commercial interest (Boswell and Collett, 2011). Additionally, gas hydrate dissociation in a marine setting risks seafloor and sub-seafloor compaction and/or destabilisation, as solid methane hydrate provides extra strength and stiffness to sediment (Uchida et al., 2012). In permafrost, compaction at depth after gas hydrate is lost is negated at the surface due to the rigidity of the overlying permafrost layer (Rutqvist et al., 2009). Other projected environmental concerns, such as disposal of the excessive produced water, are issues also faced with conventional resources (Moridis et al., 2011a). These environmental impacts could cause related social issues, if there is human development nearby.

The societal role of gas hydrate is determined by the size and development potential of the gas hydrate resource, and how development aligns with the strategic policy of the resource location (Beaudoin et al., 2014). Gas hydrate is subject to the same development considerations as any other resource, comparing net social benefit of development with any negative impact on human well-being (Beaudoin et al., 2014). Although the specific social consequences of gas hydrate development have not been researched, other unconventional gas development has associated health issues and quality of life concerns (Lozano-Maya, 2016), that may be replicated in gas hydrate development.

Since gas hydrate has yet to be proven as a technically recoverable resource, very few studies have progressed to consider if gas hydrate could be economically recoverable (Döpke and Requate, 2014; Walsh et al., 2009). Two broad concerns hindering gas hydrate development are where it is found, and the operational costs of gas hydrate production facilities (Moridis et al., 2011a). Gas hydrate resources are located offshore or in permafrost regions distant from markets, and are often associated with conventional gas (Moridis et al., 2011a), meaning there is no market opening to motivate initial development. As gas hydrate production requires constant energy input to maintain commercial production levels, gas hydrate is more expensive to develop than the conventional resources that are often coincident (Walsh et al., 2009). Development remains most viable where gas hydrate is found without other conventional or unconventional resources, such as offshore Japan.

Compared to conventional gas, gas hydrate production takes longer to reach peak production, with a lower peak value, but produces gas at commercial levels for a longer time (Moridis et al., 2011a). Although overall gas production is comparable for both operations, the lag to peak production generates an undesirable consequence in economical evaluations (Walsh et al., 2009). Most economic studies will apply discounting, where future benefits decline in value with increasing time to the benefit being realised (Attema et al., 2018). Therefore, the peak economic value of gas hydrate production will be lower than the peak value of a conventional gas development, as the peak is smaller and further away. Current economic estimation of the market price required for gas hydrate development to be commercially viable, even under the most favourable conditions, requires gas prices much higher than those observed in recent years (Nollner, 2015). Historically, gas prices have reached levels where gas hydrate commercialisation would be viable, and could again, as short term shocks could rapidly drive prices higher in specific markets (Wiggins and Etienne, 2017). As gas hydrate has yet to be technically established as a resource, there is a lack of the broader work that would be necessary before gas hydrate could be considered a reserve. Realising commercial production is only worthwhile if conditions can be found where gas hydrate can be proven as a viable commercial project, when considered to the same standard as other resources.

1.2 Aim

The aim of this thesis is to create, test and refine the first comprehensive assessment tool for evaluating a range of gas hydrate development proposals in varied settings that considers the social, economic and environmental consequences of this development.

1.3 Objectives

These are the primary objectives undertaken to meet the aim stated above:

1. Understand what tools are available for evaluating gas hydrate development proposals, and what features are necessary for a robust gas hydrate development assessment protocol.
2. Define the potential impacts from gas hydrate development socially, environmentally and economically, and suggest how each can be measured to allow comparison of different projects.
3. Improve upon existing gas hydrate modelling efforts to create numerical models that accurately quantify gas production from natural formations, and reduce the error in results caused by current model designs.

4. Understand public perception of gas hydrate development, and how stakeholder priorities will shape the future form of gas hydrate development.
5. Test the devised protocol in a range of settings where gas hydrate may be exploited, to ensure the created protocol is versatile, and ultimately understand factors influencing the future potential development of gas hydrate.

1.4 Thesis Structure

This thesis is composed of four primary chapters: a literature review, a numerical modelling chapter, a chapter detailing protocol development and initial testing, and a chapter describing versatility testing of the protocol. These chapters are followed by a general protocol summary, conclusions and suggestions for future work. Chapters are organised as scientific papers, **Chapter 3** and **Chapter 4** having been published in journals, and some material may overlap between chapters as a result. Each chapter is briefly introduced below.

Chapter 2 presents the detailed literature review completed to inform protocol development. This chapter fulfils objective 1 by exploring different structures of multi-criteria analysis that have been used in energy policy before, and the suitability of these approaches for a gas hydrate protocol. It also explains the theoretical foundation of my decision making method and the structural framework of my protocol, including preliminary definition of development impacts (objective 2). Detailed description of the protocol is reserved for **Chapter 4**.

Chapter 3 describes my numerical modelling of gas production from a range of heterogeneous distributions of gas hydrate saturation (objective 3). Modelling results were used to generate a gas production estimate with error margin for the protocol test in **Chapter 4**. This chapter implements improvements on existing modelling efforts by introducing more realistic subsurface representations. It also provides quantification of the implications of variations in gas hydrate saturation and distribution on gas production for commercial operations.

Chapter 4 is dedicated to a detailed justification for the protocol, and a step-by-step description of the protocol components necessary to evaluate a gas hydrate development proposal. As part of the protocol description, I detail the potential impacts of gas hydrate development (objective 2). This chapter also presents the results of the first practical test of this protocol, on gas hydrate development in the Alaskan Arctic, where I explored objective 4. Field testing considers the prospects of future gas hydrate development in Alaska, by consulting a cross section of society on the issue, leading to conclusions on society and the nature of development in the state. Limitations of the protocol are presented alongside proposed refinements for future applications.

Chapter 5 details three protocol tests, exploring the potential of gas hydrate development in different settings, with the aim of establishing the versatility of the protocol described in **Chapter 4** (objective 5). Three sites where gas hydrate could be developed are introduced (northwest Canada, central Siberia and offshore Japan), with explanation of why these specific sites were chosen. **Chapter 5** describes how the protocol was applied in each case study and the resulting conclusions, culminating in general findings about the suitability and flexibility of the proposed protocol.

In the final chapter the overall findings of this thesis are summarised, the final form of the protocol is described with specific considerations for each element, and limitations and opportunities for further work are suggested.

Chapter 2 Literature Review

This chapter provides a theoretical background to my study by introducing the technical components of different project evaluation mechanisms. I begin by describing the origins of MCDA within my field and its relative merits, to justify why I use a MCDA approach here. I then describe a series of MCDA techniques that have been used for similar problems, and could be used in my work, briefly introducing each, before focussing on their benefits and limitations to justify my use of the ELECTRE III method. Finally, I present a summary of common features of MCDA assessment, gathered from 104 studies in related fields that I used to inform the design of my protocol in Chapter 4.

2.1 Multi-Criteria Decision Analysis

Decision making is an inherently complex process in a world composed of multiple interconnected systems (Saaty, 1990). A decision making process should therefore create justifiable decisions, which requires a structured model (Belton and Stewart, 2002). Formalised approaches improve decision consistency and acceptance of the results by presenting a transparent decision-making process (Huang et al., 2011). Energy planning problems involve conflicting economic, environmental, technical and social factors when trying to build a cost-effective scheme with positive (or few negative) social and environmental impacts, so modelling reduces these complex, multi-factor problems into a series of accessible smaller judgements to create a clear decision-making process (Løken, 2007).

While there have been no prior appraisals of gas hydrate development, evaluation of other natural resources has used a range of methods varying in complexity, versatility and scope. Resource development involves projects that are large in scope, with significant capital outlay and development timescales, so there is interest and willingness in investing resources to select a feasible and acceptable solution (Pohekar and Ramachandran, 2004). These methods present different ways to improve understanding of a scenario, aiming to inform future decision making (Bouyssou et al., 2000). Early planning problems often focussed on value optimisation, particularly for a single criterion (Guitouni and Martel, 1998). This has evolved into multi-criteria optimisation, where values on criteria are allowed to vary freely, creating a theoretically infinite range of hypothetical alternatives. This approach remains appropriate for some problems, particularly optimising an existing system (Guillén et al., 2005). I only consider methods for choosing between defined alternatives in this work, as development alternatives are often discrete and constrained, and impact on some criteria is inherently linked (large gas production requires a certain capital investment for example), creating conflicting outcomes when all criteria are free to be optimised (Papandreou and Shang, 2008). The first criteria considered were financial, maximising return while minimising cost – the origins of cost-benefit analysis (CBA) (Pohekar and Ramachandran, 2004). Public and policy concern began to consider the impact on a wider range of criteria, beginning with growing environmental awareness in the 1980s, increasing the use of multi-criteria decision analysis (MCDA) approaches (Nijkamp and Volwahsen, 1990). Both MCDA and CBA have a similar general structure: solution *alternatives* are scored using a range of decision *criteria* that are *weighted* based on their importance to the overall decision. In a participatory process these *weights* are provided by *stakeholders.* These scores are amalgamated according to the appropriate function for the specific MCDA or CBA approach used. Both approaches are used by *facilitators* to organise information from *experts* for a *decision maker (italicised terms are defined in Table 2.1).* MCDA approaches are widely accepted and used by government entities such as the UK Department for the Environment (Department for Communities and Local Government, 2009), the US Department of Energy and US Army Corps of Engineers (Kurth et al., 2017) and NASA (Tavana, 2006).

MCDA encompasses a broad range of techniques designed for comparing alternative solutions to a decision, across a range of criteria. MCDA can include qualitative or quantitative information, and works with elicited preferences to facilitate a decision maker in reaching an informed conclusion regarding suitability of the alternatives presented (Belton and Stewart, 2002; Garmendia et al., 2010). CBA uses the net benefit of any proposal, compared to the current situation, to appraise projects, aiming for the most economically efficient resource distribution (Boardman et al., 2017).

Both methods have been applied previously to resource development evaluations, but have different strengths. CBA relies upon transforming all project information to a common monetary unit to compare alternatives (Boardman et al., 2017). MCDA is more flexible, and can include qualitative information alongside quantitative information, which is useful when dealing with impacts from different fields, and especially with impacts that are difficult to quantify in monetary terms (Martin and Mazzotta, 2018; Saarikoski et al., 2016). Particularly when used in an environmental context, there is considerable debate surrounding whether monetary evaluation is always possible or ethical (Aldred, 2006). If any costs or benefits cannot be given a monetary valuation, they become incommensurable in CBA, resulting in an incomplete evaluation (Aldred, 2006). For the broad socio-economic-environmental assessment I am aiming for, I need to go beyond monetary terms, to ensure all impacts are included, and also because limited reliable monetary information is available (Kotchen and Burger, 2007; O'Garra, 2017). CBA is perceived as less subjective than MCDA, and monetary considerations are the primary consideration for some organisations, leading to CBA being used extensively by industry or government (e.g. Ikeda, 2011; Mason, 2010). MCDA is seen as less formal and, although originally developed for expert-based assessment, less technical, which facilitates stakeholder engagement (Beria et al., 2012; Flanders et al., 1998).

Table 2.1 *Definitions of significant technical terms used throughout for describing decision analysis techniques.*

Alternatives are different mutually exclusive approaches that could be taken as solutions to the main decision under consideration (Figueira et al., 2016a).

Criteria are measurements of the performance of different aspects of each alternative in meeting the overall goals of any decision (Figueira et al., 2016a).

Weights are comparative measures of the importance of each criterion (Janssen, 1992).

Stakeholders are individuals who will be affected by the outcome of the decision, and so have a vested interest in the process, but do not dictate which alternative is chosen (Ehrgott et al., 2010). Stakeholders are considered to independently seek to maximise their utility, without considering the behaviour of other stakeholders and their likely response.

Experts are individuals who have knowledge or experience in certain criteria areas, which they can contribute to the decision making process, but do not have a vested interest in the overall decision outcome (Ehrgott et al., 2010).

The *decision maker* is the party who has overall responsibility for choosing an alternative. The decision maker is informed by the outcome of the decision making process, but is ultimately free to choose any alternative irrespective of which alternative is recommended (Figueira et al., 2016a). I am assuming a single unbiased decision maker with ultimate power over which alternative is chosen. This work focuses on structuring a comprehensive study of gas hydrate development, and does not consider possible conflicts in pursuing any given alternative that may result with multiple decision makers with competing interests (Madani and Lund, 2011).

The *facilitator* is the individual (or individuals) responsible for collating problem information and executing the decision making process to provide a recommendation to the decision maker (Figueira et al., 2016a).

Overall, the versatility of MCDA makes it more suitable for my application; MCDA methods have seen widespread use in other complex problems where there are many different stakeholder groups (Kiker et al., 2009; Mardani et al., 2017). The use of MCDA in environmental or energy planning applications has been growing in recent decades (Huang et al., 2011). The most basic approach to MCDA uses a weighted summation of the performance of each alternative against each criterion to give a total score. In most MCDA scores are replaced by utility functions, which combine scores with preference information, and utility theory assumes rational decision makers will choose the alternative that maximises utility to them (Guitouni and Martel, 1998). Some utility functions combine scores with the likelihood of that outcome being realised, incorporating risk considerations into decision making (Angelis and Kanavos, 2017). Different stakeholders will have different utility functions depending on their attitude to risk, with more risk averse stakeholders accepting lower returns with greater likelihood of realisation.

As MCDA has seen wider use there has been greater acknowledgment of the impact of uncertainties within the decision making process (Stewart and Durbach, 2016). MCDA deals with both internal uncertainties, caused by imprecisions in human judgement, and external uncertainties caused by imperfect or incomplete input data (Stewart and Durbach, 2016). Natural systems evolve over time in ways that can be difficult to predict (Mendoza and Martins, 2006). Sensitivity analysis is often used when considering how much uncertainty in the final output can be caused by uncertain input values (Saltelli et al., 1999). Specific MCDA methods have been evolved to better incorporate uncertainty in input or judgments (Section 2.2), and methods incorporating uncertainty are widely used for complex problems in the energy sector (Diakoulaki et al., 2005). Despite improving decision transparency, MCDA will not necessarily produce decisions that are socially accepted (Burton and Hubacek, 2007). MCDA is being used with conflict analysis to go beyond defining the optimum solution to understand the strategic implications of any course of action (Hipel and Walker, 2011). In conflict analysis stakeholders are assumed to maximise their individual utility while considering the likely behaviour of other stakeholders (Madani, 2010). I consider my stakeholders seeking the solution that provides greatest total benefit and make no assumptions regarding post-decision behaviour, which is an idealised representation of competitive decision problems often used by conventional MCDA studies (Madani, 2010).

Due to the prevalence of MCDA methods it is often difficult to establish which is most appropriate for a given problem. The final result can also be influenced by the choice of method, although there is generally agreement in the top ranked alternatives (Huang et al., 2011). I present further review of relevant MCDA applications in the following sections to justify my choice of method.

2.2 Common MCDA Methodologies

To understand how multi-criteria methodologies have been applied to other assessments of natural resource or energy infrastructure development, I examined 104 papers that used MCDA, focussed on recent (post-2000) works with case studies in relevant fields, such as energy policy, environmental management, operational research and environmental economics. Many of the works analysed were found through other literature reviews (Huang et al., 2011; Kiker et al., 2009; Mardani et al., 2017; Wang et al., 2009), and other works were found by keyword searching of citation indices. Papers were also selected based upon the availability of an English full text document. A full list of these papers is included in the Bibliography.

The Analytical Hierarchy Process (AHP) was the dominant MCDA method used, with pure AHP accounting for 39 studies. AHP in combination with another method, or the very similar Analytical Network Process (ANP), accounted for a further 6 studies. Other MCDA methods observed include the Simple Multi-Attribute Rating Technique (SMART), Complex Proportional Assessment (COPRAS), the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), Elimination Et Choix Traduisant la Realité (ELECTRE), Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). I briefly summarise some advantages and disadvantages of these methods in Table 2.2, and subsequently provide more operational detail on each method, to justify my choice of ELECTRE as the most appropriate approach.

There are a number of different approaches taken to classify MCDA methods. MCDA methods can be broadly divided into three types (Belton and Stewart, 2002); scoring, goal programming or outranking approaches. In scoring approaches an overall score is assigned to each alternative from overall summation of its individual scores against each criterion. Goal programming models set a desired level on each criterion and measure how close each alternative comes to achieving these goals. Outranking models are more comparative, and seek to establish the relative merit of alternatives based upon the information supporting each as better than each other alternative (Belton and Stewart 2002). These MCDA methods can also be divided into two classes (Table 2.2), compensatory or non-compensatory. Compensatory methods allow trade-offs, where poor performance on any criterion can be compensated by good performance on any of the other criteria (Guitouni and Martel, 1998). Environmental losses can be compensated by economic gains, and vice versa. By contrast, in non-compensatory methods performance trade-offs are not always possible between criteria (Guitouni and Martel, 1998). Non-compensatory behaviour aligns with strong sustainability, where there are ecological thresholds which cannot be crossed without irreparable damage (Munda, 2005; Polatidis et al., 2006).

Table 2.2 *Table briefly summarising the advantages and disadvantages of the MCDA methods assessed*.

	Type	Compensation	Advantages	Disadvantages
AHP	Scoring	Compensatory	Widely used and accepted	Requires pairwise comparison of all elements
SMART	Scoring	Compensatory	Simple Can include large amounts of information	Data uncertainty compounds in final result
COPRAS	Scoring	Compensatory	Simple	Data uncertainty compounds in final result Mathematical issues
PROMETHEE	Outranking	Non-compensatory	Uncertainty built into method	Requires high level of complex stakeholder input
ELECTRE	Outranking	Non-compensatory	Uncertainty built into method	Requires high level of stakeholder input
MACBETH	Scoring	Compensatory	Only requires qualitative judgement from stakeholders	Requires pairwise comparison of all elements
TOPSIS	Goal programming	Compensatory	Simple Can include large amounts of information	All information needs to be scalable

<u>AHP</u>

AHP is a widely used and commonly accepted decision method, applied across many scales from choosing between pipeline routes (Dey, 2004; Thomaidis and Mavrakis, 2006) to selecting between national energy policies (Kahraman and Kaya, 2010). AHP is widely used as it is relatively simple to execute, even with qualitative and quantitative information in the same study (Ramanathan and Ganesh, 1995). The decision problem is structured as a hierarchy, with a statement of the overall goal, criteria to satisfy to meet the goal, and the different alternative solutions (Saaty and Vargas, 2012). Pairwise comparison is used to produce weights for all criteria, and to compare the performance of different alternatives on each criterion individually (Saaty and Vargas, 2012). Stated preferences in pairwise comparison are converted to a numerical scale (a moderate preference is given value 3, a strong preference value 5 for example), but the conversion method used is subject to debate (Pöyhönen et al., 1997). This process homogenises data with different scales to create overall summative values for each alternative, (Saaty and Vargas, 2012).AHP has been applied with uncertain data, using concepts such as fuzzy sets or sensitivity analysis (Javanbarg et al., 2012).

Pairwise comparison of elements is simpler for stakeholders than comparing full alternatives, and so leads to more accurate preference representations (Ishizaka and Labib, 2011). However, the more information included in the assessment, the more pairwise comparisons are necessary, and the more time consuming the process becomes (Ishizaka and Labib, 2011). Comparing 4 alternatives across 11 criteria (my Alaska case presented in Chapter 4) would require 121 comparative statements. Individual pairwise comparisons can also lead to contradictory statements, with logical inconsistencies becoming more likely as the number of criteria used increases (Jeffreys, 2004). As a result it is recommended to use between 5 and 9 criteria in AHP (Mu and Pereyra-Rojas, 2017), and following this recommendation limits how comprehensive any resource evaluation can be.

SMART

In SMART, each alternative is scored against all decision criteria in a matrix. Raw scores are converted to utility functions by comparing each individual score with the full range of scores for all alternatives on that criterion (Edwards and Barron, 1994). Weights are directly assigned to each criterion, and a total score is calculated for each alternative using a weighted sum model (Edwards and Barron, 1994). Although less common than AHP, SMART has seen some use for relatively quick approximations of complex energy projects such as for decision making with UK energy policy (Jones et al., 1990), and more recently in a similar problem to my need in deciding between oil and gas projects for Petrobras (Lopes and Almeida, 2013).

One of the main advantages of SMART is its simplicity (Velasquez and Hester, 2013), but as with any weighted sum, the method is compensatory, and uncertainty will propagate through the calculation, resulting in poorly constrained final alternative scores. SMART can use both qualitative and quantitative information, although the latter will ultimately be converted to quantitative values (Chou and Chang, 2008). SMART as designed is recommended to use fewer than 12 criteria (Edwards and Barron, 1994), which is an improvement on AHP, but still limits how much can be included in a comprehensive analysis.

COPRAS

COPRAS is another additive method, but criteria to be maximised (such as gas production) and criteria to be minimised (such as capital cost) are summed separately since their aspirational values are in opposite directions (Zavadskas et al., 1994). Scores of each alternative against all criteria are collected in a decision matrix, where all values are normalised, and from there the process proceeds as two simple additive problems (Mousavi-Nasab and Sotoudeh-Anvari, 2017). The two problems are ultimately combined to assign a final utility value to each alternative, allowing alternatives to be ranked (Mousavi-Nasab and Sotoudeh-Anvari, 2017). COPRAS has been used for decision making in related fields including siting mining (Zhylinska et al., 2013) and considering environmental and social impacts in siting gas facilities (Yücenur et al., 2020).

COPRAS has similar issues to other additive methods, as uncertainties in values will propagate to the final alternative scores, resulting in large total uncertainty if using multiple sources of imprecise data, as is likely for analysing gas hydrate projects. There is also a potential mathematical issue with COPRAS, as criteria to be minimised are multiplied by weights created conventionally, with largest weight signifying highest importance (Podvezko, 2011). COPRAS has proven simple to use, even for decision problems with high numbers of alternatives and criteria, as the method has relatively few calculations steps (Mousavi-Nasab and Sotoudeh-Anvari, 2017).

PROMETHEE

PROMETHEE is a family of outranking methods. Outranking methods generally define that one alternative outranks another if it can be evaluated as at least as good as what it outranks (Figueira et al., 2016a). In PROMETHEE, a preference function is chosen to define the relationship between two alternatives on each criterion, such as the stakeholder having preference between alternatives as soon as their performance differs, or a linear increase in strength of preference with increasing separation between alternatives (Brans and Vincke, 1985). Each criterion is weighted, leading to a weighted total preference for each alternative pair, composed of information supporting one alternative outranking the other (Behzadian et al., 2010). This process is repeated for all alternative pairs to generate a complete ranking of alternatives (Behzadian et al., 2010).

Greater exploration of the preference relationship between two alternatives is the main focus of PROMETHEE, with six preference functions available to cover all possible relationships (Brans and Vincke, 1985). These preference functions enable use of uncertain information within evaluation, by allowing intermediate preference states where a stakeholder may be indifferent between two alternatives (Hyde et al., 2003). PROMETHEE is non-compensatory, and so can allow partial ranking of alternatives, retaining more information than if alternative performance is aggregated to a single score (Macharis et al., 2004). As a different preference function is specified for each criterion, qualitative and quantitative information can be used concurrently within the same study (Cinelli et al., 2014). PROMETHEE has a lot of potential for bespoke customisation to new energy technologies (Monds, 2013; Oberschmidt et al., 2010) and has also been used extensively within environmental management (Behzadian et al., 2010), where limits on compensation are highly relevant.

The main disadvantage of PROMETHEE is that it requires significant external input to complete the evaluation, as a preference function is required for each alternative pair, in addition to weights for all criteria. Methodologically, creation of the preference functions in PROMETHEE from external input is unclear (Velasquez and Hester, 2013). As a result, the method can prove difficult for non-experts to use (Kumar et al., 2017), limiting stakeholder involvement.

ELECTRE

ELECTRE is another family of outranking decision analysis methods. For each criterion, thresholds define the point at which one alternative is preferred to another based upon the difference in performance between alternatives (Figueira et al., 2013). These preference relationships are used to create universal measures of how dominant each alternative is, and in turn how much each alternative is dominated, leading to a ranking of alternatives by overall superiority, although this ranking does not have to be complete (Figueira et al., 2013). ELECTRE is common when considering water or energy management with conflicting stakeholder groups (Govindan and Jepsen, 2016) and has some precedent in considering the viability of new energy technologies (Peng et al., 2019).

ELECTRE allows qualitative criteria to retain their natural scales, enabling decision making using diverse criteria, including ordinal or descriptive information (Figueira et al., 2013). ELECTRE is also non-compensatory, and allows alternatives to be discounted due to excessively poor performance on any criterion by the use of a veto (Figueira et al., 2013). As a result ELECTRE will not recommend an otherwise well-performing alternative with very poor performance on a single criteria. The thresholds also explicitly allow uncertain data to be included, by enabling situations of indifference between alternatives (Cinelli et al., 2014). Use of ELECTRE is mainly limited by its complexity, with a high level of technical expertise expected of the facilitator and the stakeholders, as the latter must provide a series of weight and threshold values that can be difficult to conceptualise (Velasquez and Hester, 2013). As a result ELECTRE can be disliked by some decision makers who consider it a ‘black box’ approach, and so may be less likely to accept its recommendations (Haralambopoulos and Polatidis, 2003).

MACBETH

For each of the criteria used in MACBETH the decision maker establishes two reference levels, corresponding to most and least attractive theoretical performance (Costa et al., 2003). Individual performances are converted to value added from changing between the reference levels and the actual performance levels of each alternative, and these individual values are summed into a global attractiveness of each alternative (Costa et al., 2003). Stakeholders express a preference between pairs of alternatives or criteria to determine weights using descriptive categorical statements. MACBETH software automatically converts these statements to criteria weights, while continually checking global consistency of all stakeholder responses (Costa et al., 2003). MACBETH is a less common decision support method because its use is strongly tied to a relatively opaque software, but has proven a useful tool in studies with limited quantification for most criteria and distinct stakeholder groups (Burton and Hubacek, 2007; Mateus et al., 2017).

MACBETH is considered accessible to stakeholders as no precise quantitative judgements are required, although stakeholders wishing to provide quantitative values cannot, even if they are sufficiently knowledgeable to do so. The qualitative judgement process also makes MACBETH time consuming, as a large number of qualitative judgements are required from each stakeholder through pairwise comparison of all elements (Santos et al., 2014). MACBETH readily incorporates qualitative and quantitative information when defining alternatives (Guarini et al., 2018).

TOPSIS

TOPSIS ranks alternatives by closeness to a hypothetical perfect solution, and distance from a hypothetical worst solution (Tzeng and Huang, 2011). TOPSIS begins by normalising all alternative values in a decision matrix, and multiplying these values by the corresponding criteria weights (Tzeng and Huang, 2011). The best values from each criteria are combined to give a hypothetical ideal alternative, and the worst values are combined to give a hypothetical worst alternative. All decision alternatives are ranked by similarity to the former and separation from the latter (Tzeng and Huang, 2011). TOPSIS is commonly used when looking for small improvements in existing systems, as solution can be positioned between the current situation and the hypothetical best case, and has been used for optimising energy generation in this way (Behzadian et al., 2012).

There is fundamental debate surrounding TOPSIS using closeness to the ideal solution and distance from the worst solution equally, as the preferred solution may be the closest to the ideal solution, irrespective of the worst possible solution (Opricovic and Tzeng, 2004). By using Euclidean distance TOPSIS is fully compensatory (Guitouni and Martel, 1998). TOPSIS can use both qualitative and quantitative criteria in a study, although all data needs to be scalable (Løken, 2007). To accommodate uncertainty, TOPSIS can represent imprecise alternative values or criteria weights with fuzzy sets (Ashtiani et al., 2009). The method is fundamentally simple to explain and execute, as TOPSIS only requires stakeholders to provide weighting information (Özcan et al., 2011). The simplicity of the process also allows TOPSIS to be used with large numbers of criteria and alternatives (Guarini et al., 2018).

Summary

The relationships and trade-offs implied by a compensatory model, such as possible exchange of natural capital for financial capital, are not acceptable to all stakeholders (Munda, 2005). Trading losses to one group for benefit to a different group has social justice concerns (Sovacool et al., 2016). In multinational resource development in a global economy, negative impacts are often disproportionately felt by those in the area of resource development rather than those deriving benefit from the resource at end use, such as the increased impact of fossil fuel emissions on warming in the Arctic (Gjørv, 2017), or the livelihood impact of the Exxon Valdez oil spill during oil export from Alaska (Kolk, 2016).

As such, I judge that a non-compensatory approach is necessary for this situation. Of the methods within my review, only ELECTRE and PROMETHEE use non-compensatory behaviour, and the ELECTRE procedure is more clearly defined. The advantage of an outranking approach is that it greater enables uncertainty in stakeholder judgement by use of indifference. In this way outranking can be argued to more realistically represent the preference attitude of human decision makers, where there is a range of values where a stakeholder may be unsure of submitting a firm preference for either alternative (Mendoza and Martins, 2006).

ELECTRE allows me to use imprecise qualitative and quantitative information, which is useful as the current infancy of gas hydrate development means there is very limited information available (Figueira et al., 2013; Kangas et al., 2001). What information is available has been measured in many different ways, needing a method such as ELECTRE that can use data in natural scales. The main concern with using ELECTRE is the high level of technical knowledge required for completing an assessment by this process, but literature on the method and its application in related fields is available. Therefore I believe ELECTRE is the most appropriate method for this problem, and is technically suitable for the available resources.

2.3 The ELECTRE III Method

As ELECTRE is my chosen MCDA method, within this section I describe the ELECTRE process in more detail. When describing ELECTRE notation used throughout is: A_1, A_2 … A_n are a set of n alternatives, which are potential solutions to a multi-criteria decision-making problem. X_1, X_2 … X_m are a set of m criteria used to assess the performance of the alternatives. $f_X(A_n)$ is the performance of alternative n against criterion x. An impact matrix is used to structure the problem, with alternatives given in columns and criteria given in rows, and cells providing $f_X(A_n)$ values.

ELECTRE is a family of outranking methods which seeks to establish whether A_1 is not inferior or better than A_2, and so outranks it. ELECTRE II and ELECTRE III are ELECTRE variants designed to rank alternatives from best to worst (Roy, 1977). ELECTRE III is an improved version of ELECTRE II that better incorporates inaccurate or uncertain data (Figueira et al., 2016b), and is now the most commonly used method from the ELECTRE family (Govindan and Jepsen, 2016). In outranking models, if A_1 is superior, the amount by which it outranks A_2 is not important, hence some imprecision in impact values will not affect the overall result (Figueira et al., 2013).

ELECTRE uses pairwise comparison of two alternatives on a criterion by criterion basis to establish whether a strict preference relationship exists between alternatives. ELECTRE III uses three types of thresholds when comparing alternatives, illustrated below for criteria to be maximised (Dias et al., 2006):

1. Indifference (q). The indifference threshold, q, defines the maximum difference in impact between two alternatives, A_1 and A_2, on a given criterion x, for which the stakeholder is indifferent between the two alternatives. The stakeholder is indifferent between A_1 and A_2 as long as the relationship holds that $f_x(A_2) < f_x(A_1) + q_x$. Indifference allows imprecise, imperfect data to be used (Figueira et al., 2013). For example, a stakeholder is likely to be indifferent between two alternatives whose difference in performance is less than the error margin in measurement of that performance.
2. Preference (p). The preference threshold, p, is the minimum value above which a stakeholder has a strong preference for one alternative on a given criterion x. A_1 is preferred to A_2 on criterion x if $f_x(A_1) \geq f_x(A_2) + p_x$. Between the indifference and preference thresholds is a zone of weak preference where a stakeholder hesitates in providing a strict preference as the difference in performance is still low, and their decision may be affected by other factors (Mendoza and Martins, 2006).
3. Veto (v). The veto threshold, v, can block overall outranking, as one alternative cannot outrank another if it is inferior by the veto threshold or higher on any criterion. If $f_x(A_2) \geq f_x(A_1) + v_x$, A_1 cannot outrank A_2. Vetoes prevent recommendation of an alternative with very poor performance for any criterion, even if it has favourable performance from all other criteria (Løken, 2007).

ELECTRE calculates outranking through comparing the performance of each pair of alternatives against these three thresholds (Rao, 2013). For the three thresholds, $v \geq p \geq q$.

The ranking of alternatives is developed through two elements, concordance and discordance (Figure 2.1). Concordance and discordance both calculate indices with values between 0 and 1. The total concordance C between two alternatives (A_1 and A_2) is the weighted sum of the concordances of A_1 as not inferior to A_2 for each individual criterion (c_x), where there are N criteria in total. W represents the total weight of all criteria and w_x represents the weight of criterion x. The formula for concordance is given in Equation 1.

$$C(A_1, A_2) = \frac{1}{W}\sum_{x=1}^{N}(w_x \times c_x(A_1, A_2)) \; where \; W = \sum_{x=1}^{N}(w_x) \quad \textbf{Equation 1}$$

In Equation 1, $c_x(A_1,A_2)$ is the concordance of A_1 as not inferior to A_2 on criterion x, given by Equation 2.

$$c_x(A_1, A_2) = \begin{cases} 1 & f_x(A_1) + q_x \geq f_x(A_2) \\ 0 & f_x(A_1) + p_x \leq f_x(A_2) \\ \frac{p_x + f_x(A_1) - f_x(A_2)}{p_x - q_x} & otherwise \end{cases} \quad \textbf{Equation 2}$$

The discordance index (Equation 3) measures how much information supports A_2 as superior to A_1, with total discordance aggregated over all criteria. The veto threshold means that A_1 as superior to A_2 can be rejected completely, if the alternative which would be outranked is superior by more than the veto threshold on any criterion.

$$d_x(A_1, A_2) = \begin{cases} 0 & f_x(A_1) + p_x \geq f_x(A_2) \\ 1 & f_x(A_1) + v_x \leq f_x(A_2) \\ \frac{f_x(A_2) - f_x(A_1) - p_x}{v_x - p_x} & otherwise \end{cases} \quad \textbf{Equation 3}$$

The next step is creating a credibility index between two alternatives, $K(A_1, A_2)$ (Equation 4), which combines the concordance and discordance indices. Credibility compares the overall concordance score with each of the discordance indices. If $c_x(A_1, A_2) > d_x(A_1, A_2)\ \forall x$, then $K(A_1, A_2) = C(A_1, A_2)$. Otherwise, the credibility index must be calculated from the concordance score and the product of the ratio of the discordance indices to the concordance score (Equation 4). An overall credibility near 1 supports the hypothesis of A_1 as not inferior to A_2, a credibility near zero opposes the hypothesis, and a value between suggests neither alternative is strongly superior to the other (Li and Wang, 2007).

$$K(A_1, A_2) = \begin{cases} C(A_1, A_2) & d_x(A_1, A_2) \leq C(A_1, A_2),\ \forall x \\ C(A_1, A_2) \times \prod_x \frac{1 - d_x(A_1, A_2)}{1 - C(A_1, A_2)} & otherwise \end{cases} \quad \textbf{Equation 4}$$

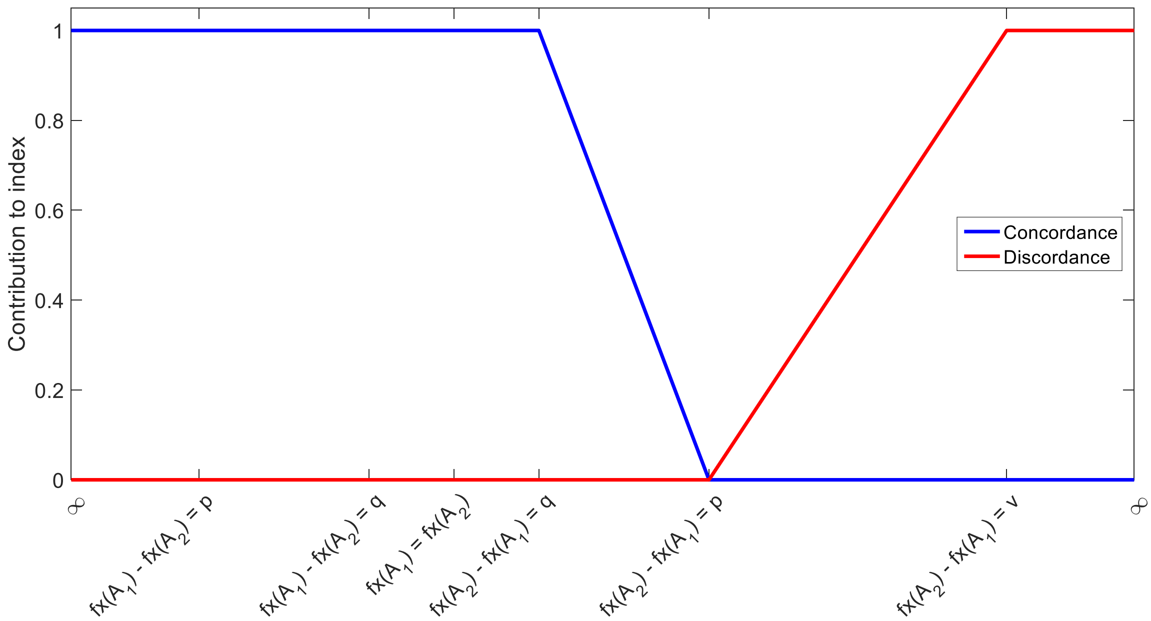

Figure 2.1 *Contributions to concordance and discordance indices under certain conditions of preference between two alternatives. The x-axis represents the difference between the performance of two alternatives on a single criterion. This graph represents continuous, numeric data for a criterion where higher values are preferred.*

The final step is to use the credibility matrix to rank alternatives, by calculating a superiority ratio (Equation 5). The overall superiority, *S*, of each of the n alternatives is a ratio between the sum of the credibility of a given alternative (A_1) as superior to other alternatives (A_2 to A_n) and the sum of the credibilities of all other alternatives as outranking the given alternative. The larger this ratio is, the more dominance exhibited by an alternative.

$$S(A_1) = \frac{\sum_{m=2}^{n} K(A_1, A_m)}{\sum_{m=2}^{n} K(A_m, A_1)} \qquad \textbf{Equation 5}$$

As ELECTRE is a mechanism for ranking alternatives, Arrow's impossibility theorem (Arrow, 1951) states that ELECTRE cannot simultaneously achieve unrestricted domain (all possible preferences can be expressed), independence of irrelevant alternatives (A_1 remains preferred to A_2 if a third alternative A_3 is added or removed from the alternative set), unanimity (if A_1 is preferred to A_2 by all individuals, the method will prefer A_1 to A_2 overall) and non-dictatorship (collective preference is not solely dependent on the preferences of one individual). Unrestricted domain is the most important property for ELECTRE to successfully satisfy, as unrestricted domain ensures that each stakeholder response can be translated into a complete preference order (Geanakoplos, 2005). Fulfilling unanimity and non-dictatorship make ELECTRE participatory, as the final result depends on all stakeholders' input, and if all stakeholders provide the same information, this preference will be reflected in the final alternative ranking. As such, rankings derived by ELECTRE fail to show independence from irrelevant alternatives (Wang and Triantaphyllou, 2008). However, adding or removing alternatives changes the decision problem, so changes to the overall rank may reasonably result. Mathematically, changes to the alternatives present may alter the calculated preference and indifference thresholds, which suggests these values are dependent on the problem context (Figueira et al., 2013). As a result, adding, altering or removing alternatives during any decision may alter the end results. Additionally, this rank reversal of alternatives may indicate that data quality is too poor for a non-ambiguous solution to the decision problem (Figueira and Roy, 2009). For example, adding an alternative with poorly defined error margins will increase indifference thresholds throughout, potentially removing discriminatory power between other alternatives. Also following Arrow's theorem, outranking is not transitive, so preferences in ELECTRE are not necessarily complete (Figueira et al., 2013). A_1 can be preferred to A_2, and A_2 can be preferred to A_3 but A_3 still preferred to A_1 (the Condorcet paradox (Gehrlein, 1983)). Since alternative pairs are considered in isolation within ELECTRE, nothing can be inferred about preference towards another alternative from comparing a pair without that alternative (Bouyssou et al., 2000). However, transitivity does not always logically hold (Luce, 1956). Transitivity is valid when amalgamating the preferences of individuals to form a group opinion, as the majority of people may prefer A_1 to A_2, A_2 to A_3 and A_3 to A_1, but the individuals composing the majority differ in each case. As incomparability is allowed in outranking theory, incomplete preference is possible, whereas other methods must create a full series of preference relationships, even if alternatives have major differences (Doumpos and Zopounidis, 2006).

2.4 Criteria and Alternatives

In addition to reviewing the MCDA methods used in the 104 papers mentioned in Section 2.2, I also explored how these studies introduced alternatives and criteria. 95 of the included studies had defined lists of alternatives, with 9 studies not including a case study with discrete alternatives. There is a considerable range in the number of criteria per study, with 24 studies using five or fewer, 31 five to ten, 21 ten to fifteen, 14 fifteen to twenty and 14 over twenty. Generally, most applications of MCDA involve small numbers of thoroughly defined alternatives, (79% of those examined used ten or fewer, with 46% using five or fewer) and therefore this approach is taken when structuring my assessment.

A wide variety of criteria were observed, dependent on the priorities of the specific study. From comparing studies I defined five broad criteria groups: Resource Information, Economic, Social, Environmental and Infrastructure. Resource Information criteria were very case specific measurements of geoscientific information at a given location, and so were not examined in further detail as there is little comparability between studies. In my study I used numerical modelling to quantify resource information (Chapter 3), modelling gas production based on the specific characteristics of the study site. The economic, social and environmental criteria are commonly referenced in similar projects: economic criteria cover impacts measured in monetary units; social criteria cover impacts on the human environment; and environmental criteria cover impacts on the natural environment. Infrastructure criteria measure impacts which fit poorly into other criteria, such as technological or legal factors. The most common approach observed in the reviewed works was to include all four criteria groups considered (economic, social, environmental, infrastructure), as shown in Figure 2.2. In some instances a single criterion is used to encompass all impacts in that area, especially for environmental impact (e.g. Cherni et al., 2007; Gough and Shackley, 2006; Stein, 2013; Thomaidis and Mavrakis, 2006).

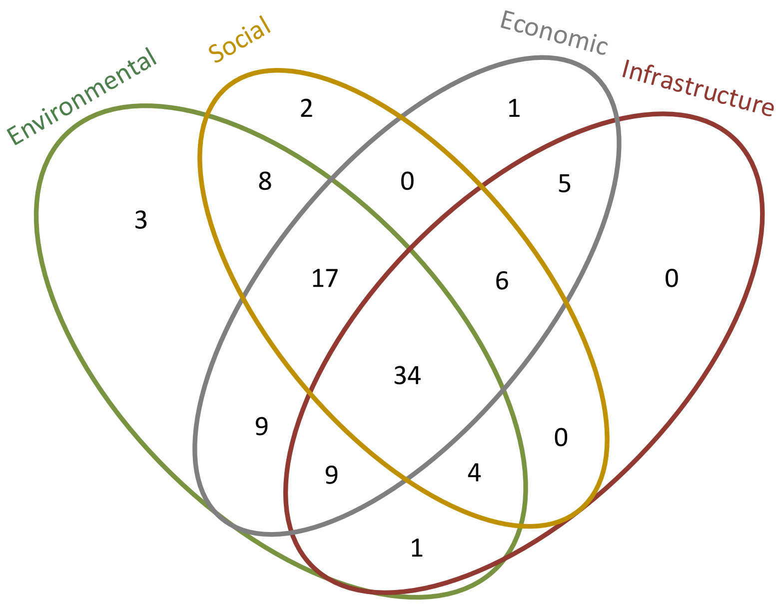

Figure 2.2 *Distribution of criteria used in 99 literature review papers which included criteria in at least one of these four defined areas. 5 studies only include resource information, and so are not displayed. Numbers indicate how many studies used that combination of criteria for evaluation. Overlap indicates that both criteria were used.*

Fourteen studies included no environmental criteria, eighteen included no economic criteria, and twenty-eight included no social criteria. Air pollution was the most common specific environmental indicator, which was usually quantified by emissions of gases such as CO_2, NO_x or SO_2. This criterion was included in 39% of all studies, and in many cases was the only environmental indicator used (e.g. Papadopoulos and Karagiannidis, 2008; Tsoutsos et al., 2009; van Alphen et al., 2007). This criterion was chosen because of the relative ease with which it can be quantified, and because emissions targets are an often included in organisational policy (St. Denis and Parker, 2009). Other forms of pollution, such as aesthetic (11%) or noise (9%) were much less frequently included as impacts, suggesting much lower prioritisation. Effects on habitats were only measured in 18% of studies, and impacts on specific species populations were only measured in 11%. These low values suggests avoidance of criteria which are difficult to quantify.

The most common social criterion is employment (26%), which is a common consideration of industry or governance when reviewing project proposals. This criterion is also relatively easy to quantify, especially compared to other social criteria such as impacts on cultural assets (4%), as cultural assets includes sites of religious or historical importance, or local customs, languages and religions (Bagočius et al., 2014; Tavana et al., 2013). Also regularly included as a criterion was impacts on human health (20%). Another social criterion used was social perception (17%), which was used to indicate stakeholder attitudes towards the alternatives without including direct stakeholder input elsewhere in the MCDA, such as in the weighting (Kiker et al., 2009).

Economic criteria were often included, but the main economic consideration varied between studies. In some studies the primary concern was total cost (21%), in others there was differentiation between initial capital costs (24%) and operational costs (32%). Other studies instead measured profitability or net present value (NPV; 24%). 12% of studies included market considerations such as market size, volatility or competition. Economics are of primary importance in most business cases, and can be quantified, so their widespread inclusion is unsurprising.

I use the designation of infrastructure to encompass physical, governmental and regulatory infrastructure. Technological factors were often included in the examined studies (20%), and reliability of the production equipment (11%) appears to be considered more important than lifespan (4%), especially in energy policy. Project construction duration was also rarely included (4%), which may result from this value not differing significantly between alternatives within any single study. Existing or planned physical infrastructure was considered in 19% of applications. Finally, 15% of studies included some measure of how alternatives would be helped or hindered by legislation.

Since gas hydrate production is not presently occurring, there is considerable uncertainty in possible gas hydrate-specific impacts that may require specific criteria to evaluate. To fill this gap, possible impacts are formulated using a DPSWR (Drivers-Pressure-State-Welfare-Response) framework (Figure 2.3; Cooper, 2013, 2012). DPSWR is a development of DPSIR (Drivers-Pressure-Impact-Welfare-Response) to reduce ambiguity in the definitions of the five main elements (Cooper, 2012). Drivers are activities undertaken to improve human welfare. Drivers exert Pressure on a system, with intended and unintended consequences. The environmental State is altered by this Pressure, causing a change in human Welfare. Sections of society then Respond to this change in Welfare, creating new Drivers (Cooper, 2012; Smeets and Weterings, 1999). This approach allows the creation of causal chains to theorise impacts from human activity on an interacting human and natural system (Gari et al., 2015). I used the DPSWR framework to hypothesise specific impacts on the natural environment from gas hydrate development. Gas hydrate development that produces gas for human use is a Driver, but this creates an unexpected Pressure as the gas hydrate acts as a rigid layer in the subsurface, but this layer is lost as the gas hydrate dissociates. As a result the natural environment changes State as strong layers become substantially weakened, and these weakened layers may impact Welfare, as structures become damaged by the surface subsiding. The Response to this risk to infrastructure may be limitations on where drilling can occur. This DPSWR approach was used to complete the list of criteria measuring the impacts of development (Section 4.3.4), in addition to relevant criteria transferred from my literature review.

From literature review and DPSWR theorising I have a list of potentially relevant criteria to consider for inclusion within my protocol, as well as how commonly each is used, and methods by which each can be evaluated. These criteria are presented and described in further detail in Chapter 4.

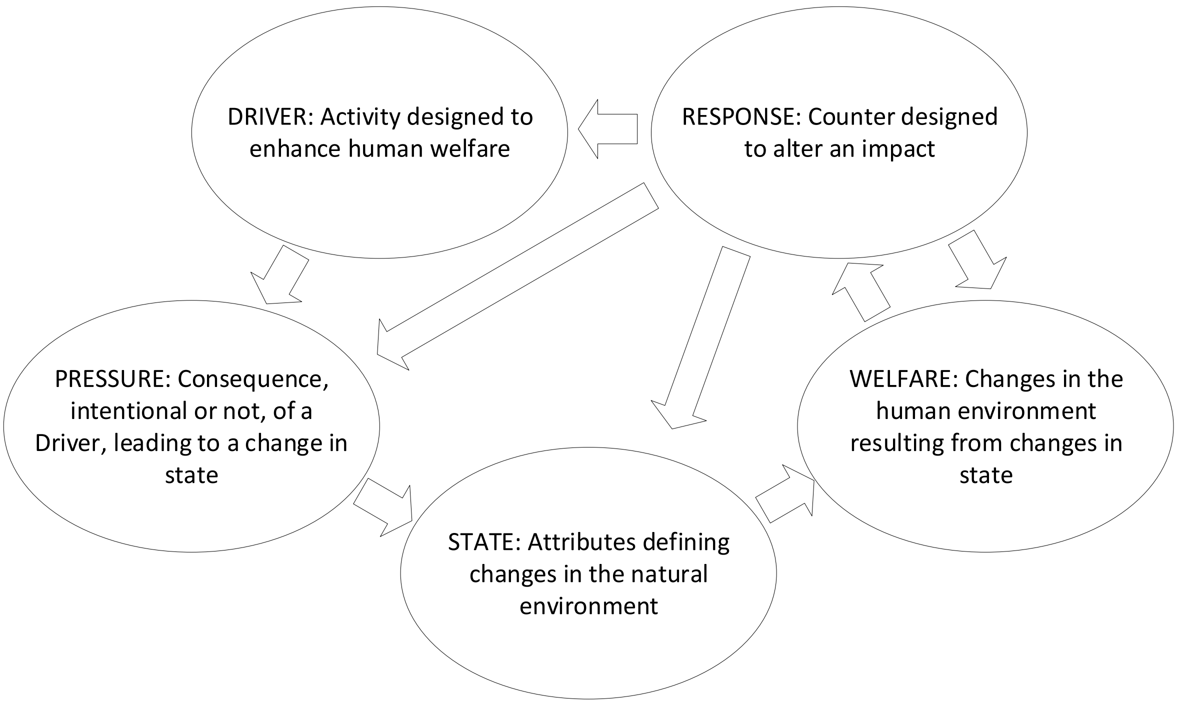

Figure 2.3 *The DPSWR framework (Cooper, 2013).*

2.5 Weighting

Weighting to establish preference is a feature common to MCDA applications. The studies reviewed lack consensus on the method used to derive these weights, or who should provide them. In many studies weights are provided directly by stakeholders or experts simply scoring or stating the criteria most important to them (33% of all studies), but not all studies make a distinction between experts and stakeholders, or clarify if a specific weighting method has been used. As it is rare that all stakeholders can provide weights directly, as this approach requires high technical understanding from all stakeholders, methods for deriving weights are often used with MCDA. Pairwise comparison was the most commonly encountered method (24%), as this method is suggested for weighting in AHP, the most commonly used MCDA method. However, AHP weighting can be completed by the facilitator, the decision maker, all stakeholders or just a shortlist of experts, depending on the application. Another weighting method used is swing weighting (5%), where preference is expressed on which criterion is changed from worst possible to best possible values, and criteria are weighted by the order in which they are swung (Lopes and Almeida, 2013). Swing weighting is simple to apply, but is criticised for only using extreme values, creating hypothetical alternatives with extreme properties that can be difficult for stakeholders to understand (Troffaes and Sahlin, 2017). In some cases multiple hypothetical weight allocations are used within one study to reflect different priorities, and then these results are compared (7%) (e.g. Afgan et al., 2007; Balogun et al., 2015; Beccali et al., 2003). An alternative philosophy involves calculating weight ranges for criteria for which each alternative would be preferred (Miettinen and Salminen, 1999). Both of these approaches are simpler than other weighting schemes, as they require no external stakeholder input, but both also produce hypothetical results that may not reflect real world opinions. In Chapter 5 I use scenario analysis with multiple series of hypothetical weights, to enable completion of more case studies in the available time. I ground my hypothetical weights in real-world opinions, by basing hypothetical weights on the range of weighting encountered during my Alaska case study (Section 4.4).

No specific weighting scheme is defined for ELECTRE (Özcan et al., 2011), so many have been used, including direct allocation by experts or decision makers (e.g. Wen et al., 2016; Wu et al., 2016), swing weighting (e.g. Balasubramaniam et al., 2007), Simos' method and revisions (e.g. Figueira and Roy, 2002) and hypothetical weights (e.g. Kumar et al., 2016). In Simos' approach, cards are used to physically represent each criterion. Stakeholders order the cards based upon their priorities in deciding between alternatives, with equal importance criteria grouped. Additional blank cards are used to separate criteria to represent differences in importance between them (Simos, 1990). However, the numerical conversion in this procedure may lead to weights which do not match the decision maker's preference, where the difference in weight between successive criteria is inconsistent, as it is influenced by the total number of criteria cards and blank cards used (Figueira and Roy, 2002). This criticism has led to a revised Simos' procedure, with different formulae for converting card positions to weights, that maintains consistency between the separation in cards and the separation in numerical weights (Figueira and Roy, 2002; Govindan and Jepsen, 2016). In the revised Simos procedure, weighting are based upon the intrinsic qualities of the criteria, not just the current decision context, which is significant as I am using hypothetical development alternatives to find stakeholders' priorities, so I want stakeholders to consider whether criteria are important to them generally, beyond the decision context in which they are presented. Practically, Simos' approach is relatively easy to apply, and derives quantitative information from stakeholders providing ordinal data instead of precise values directly. I have chosen the revised Simos' procedure due to its accessibility to many different stakeholders and prior use with ELECTRE.

2.6 Conclusion

From considering its prior application and development I conclude that MCDA is an appropriate approach for this problem, as it encourages stakeholder participation, and can include a wider range of impact information without incommensurability issues. There are many specific MCDA methods that have seen prior use in similar energy policy or planning problems, so I evaluated 104 papers in resource development and energy policy to establish the suitability of each major method. I choose to develop a protocol using the ELECTRE method (Section 2.3), as ELECTRE can use the imprecise data present at the current early stage of gas hydrate development, and ELECTRE allows non-compensatory behaviour. I also use this literature review to broadly suggest impacts of gas hydrate development, by exploring which impacts are comparable in conventional development, and by using the DPSWR framework to propose impacts specific to gas hydrate development. Overall impacts fall into five categories (Resource information, Economic, Social, Environmental and Infrastructure). As there is no single impact weighting method within ELECTRE, I have reviewed the range of methods previously applied, and decided to use the revised Simos' procedure, due to its simplicity and consistency in using with diverse stakeholders.

Chapter 3 The effect of Heterogeneities in Hydrate Saturation on Gas Production from Natural Systems

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Understanding the rate and time evolution of gas release from natural gas hydrate systems is important when evaluating the potential of gas hydrate as a future energy source, or the impact of gas from hydrate on climate. The release of gas from hydrate is heavily influenced by a number of factors, many of which vary through the hydrate system. The fundamental heterogeneity of natural gas hydrate systems is often poorly represented in models. Here we simulate depressurisation-induced gas production from a single vertical well in 34 models with heterogeneous 2D distributions of hydrate that include layered, columnar or random configurations and comparable models with homogenous saturation distributions. We found that the temporal evolution of gas production rate follows a consistent trend for all models, but at any time the gas production rate across the models varied by up to ±35% in the first year of production, and by up to ±25% thereafter. The primary control on the gas production rate is the overall amount of hydrate in the system, but local variations in hydrate saturation cause significant fluctuations in the time evolution of production. These hydrate variations can cause changes in the gas flow path through the system and associated drops in gas production rate continuing for multiple years. Overall, our results suggest that small levels of heterogeneity in hydrate systems can cause variations in the gas production rate similar in scale to much larger variations in homogenous systems. Our work provides an error margin for previously modelled gas production rates, and a note of caution for potential commercial development of gas hydrate.

3.1 Introduction

There is ongoing global interest in the potential development of gas hydrates as an unconventional energy source, to contribute to growing global demand of cleaner fossil fuel resources. Gas hydrates are solid-ice compounds containing molecules of gas, normally methane, within voids in regular crystalline structures (Sloan and Koh, 2007). This structure enables each cubic metre of gas hydrate to contain up to 180 cubic metres of gas at standard pressure and temperature conditions, that can potentially be released through conventional technology, making hydrate an energy-dense fuel source (Sloan, 2003). Gas hydrates form in hydrocarbon systems at high pressures and low temperatures. Accordingly, natural hydrates are found primarily onshore in permafrost areas and offshore beneath continental slopes and deep waters. In polar areas, because of their low seabed temperatures, hydrate can be found in relatively shallow waters. The global volume of recoverable gas contained within gas hydrates is believed to be comparable in scale to global conventional gas resources (Chong et al., 2016). This abundance has motivated pilot testing of natural gas production from hydrates in prominent markets including Japan, China and the United States (Anderson et al., 2014; Konno et al., 2017; Li et al., 2018).

Numerical simulation of gas production from hydrate reservoirs is used as with conventional resources, to test production schemes and determine the productivity of specific reservoirs. Several simplifications are made when approximating real-world hydrate provinces with numerical models, including the representation of the hydrate-bearing domain. Complex distributions of hydrate are frequently modelled as a homogenous volume (e.g. Kim et al., 2018; Yan et al., 2018; Yu et al., 2018; Zheng et al., 2018), or as a sequence of layers with constant hydrate saturation (e.g. Chen et al., 2018a; Feng et al., 2019; Yuan et al., 2017). Natural systems rarely display this level of homogeneity, as small compositional variations or structural irregularities will alter how hydrate is distributed (Behseresht and Bryant, 2012). Some recent modelling seeks to improve accuracy to the real world by introducing heterogeneity based upon available well data (Ajayi et al., 2018; Jin et al., 2018). However, there has been limited study on how significant modelling assumptions on hydrate saturation are for final production values (Bhade and Phirani, 2015; Nandanwar et al., 2016; Reagan et al., 2010). Techniques for quantifying subsurface hydrate also carry some error (Riedel et al., 2010), so even a perfect model of available data may be subtly different to the real world situation it is representing.

Our chosen model environment is the Alaskan Mount Elbert system, a cold, multi-layered hydrate formation onshore beneath the Prudhoe Bay area of the Alaskan North Slope. We use this site because it has been the subject of hydrate research for almost 50 years (Collett et al., 2011a), has well log data available, and there are published modelling studies with which we can compare our results (Hunter et al., 2011). Previous models suggest that the commercial potential of this hydrate system is low (Moridis et al., 2011b). Here we focus on providing general, process-based insights into the effect of hydrate saturation heterogeneity on gas production and do not seek to optimise the production process. We explore hydrate saturation as it has a direct impact on whether a gas hydrate reservoir is considered a prospective target (Boswell et al., 2015), and also alters the hydrological and thermal response of the system (Tamaki et al., 2017). Our work provides insight into how heterogeneity affects gas production and the associated implications for future hydrate exploitation.

3.2 Methods

We used the TOUGH+Hydrate simulator for multi-phase fluid and heat transport in gas hydrate bearing media. TOUGH+Hydrate models hydrate dissociation or formation, as a kinetic or equilibrium process, and the associated phase changes amongst four possible phases (gas, liquid, solid-ice, solid-hydrate). We assumed an equilibrium hydrate reaction, as it is less computationally intensive while giving very similar results on our modelling scale (Kowalsky and Moridis, 2007). TOUGH+Hydrate can simulate three production methods or combinations thereof, depressurisation, thermal stimulation or the use of an inhibitor (Moridis, 2008) and has been used extensively in similar hydrate modelling problems, thus validating our approach (Li et al., 2016).

Gas hydrate has been encountered throughout the North Slope in six units (designated A-F), which range from metres to tens of metres thick (Collett, 1993). Our model includes the two hydrate bearing layers that were cored in 2007 (Hunter et al., 2011), C and D, with unit D used as the primary model production target (Figure 3.1). We have used existing well log data and production simulation parameters as the basis for our modelling (Table 3.1). Unit D is a 13.4 m thick gas hydrate bearing layer at 616.4–627.9 m depth, and unit C is a 16 m gas hydrate bearing layer from 650–666 m depth, with some layered structure with significantly lower hydrate saturation than the unit overall (Collett et al., 2011b). Gas hydrate saturation in the layers has been estimated at 50–80% from resistivity modelling, acoustic and shear wave velocities and core sampling (Collett et al., 2011b). For our baseline homogeneous model we chose 55% saturation as representative for unit D, and 50% saturation for unit C. We conducted two other homogeneous tests with saturations ±5% from these values. In our heterogeneous models saturation varied between 30–70%. We assumed the non-hydrate-bearing layers to be fully aqueous saturated initially.

Our model uses an evolving porous medium approach, in which hydrate changes affect the intrinsic permeability of the medium but not the capillary pressure. Relative permeability and capillary pressure are controlled by the equations and parameters given in Table 3.1. Irreducible phase saturation (S_{ir}) is the finite minimum saturation of a fluid phase that cannot be displaced by another phase (Ahmed, 2019). It is set at different values for the relative permeability and capillary pressure equations as required computationally (Moridis, 2008). n, n_g and λ are empirical fitting parameters derived through laboratory tests for the Stone (Stone, 1970) and van Genuchten equations (van Genuchten, 1980). P_0 is the gas entry pressure required to enter pores

(Mahabadi et al., 2016). We have used values of these specific parameters that are equal to those used in previous studies on Mt Elbert to allow our results to be compared. We recognise that experimental studies suggest different values for some of these parameters (Mahabadi et al., 2016; Mahabadi and Jang, 2014).

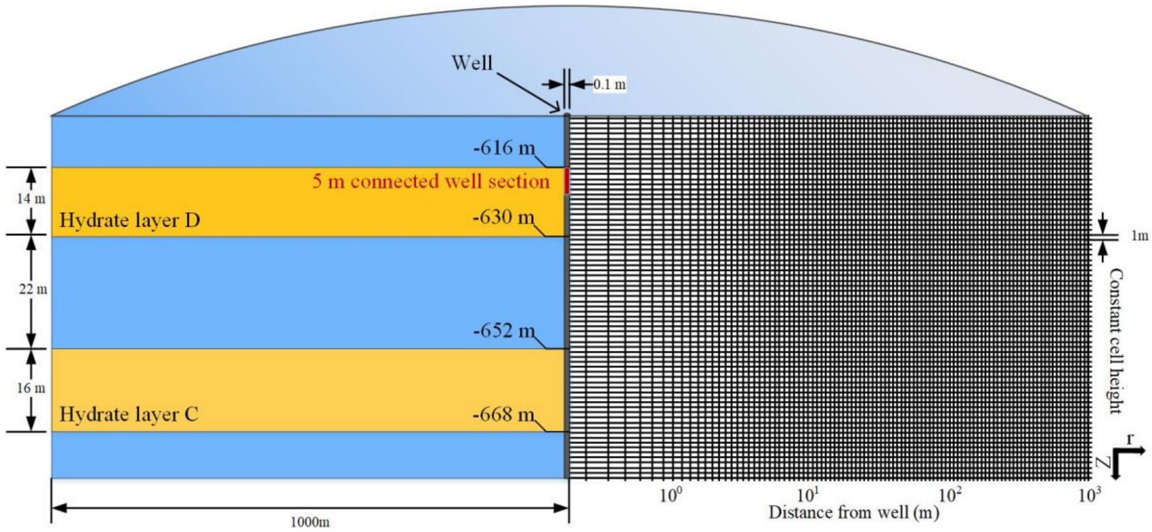

Figure 3.1 *Schematic diagram of our 2D radially symmetric model used (left) and the numerical mesh used (right). Note that the variation in cell size in the radial axis is on a logarithmic scale.*

The model domain is a 2D radial section (r,z) composed of 7622 cells (Figure 3.1). In the z-axis the model is 72 cells high, each cell being one metre in height. Radially, cell width varies logarithmically from tens of centimetres adjacent to the well, to tens of metres at the maximum model radius, 1000 m away from the well. The well cells have a width of 0.1 m, commensurate with the wellbore radius. The well is represented by a pseudo-medium with high porosity (100% pore space) and a relatively low permeability (≈1×10^{-12} m^2). The well is only connected to the formation in the uppermost 5 m of the hydrate bearing layer D (Figure 3.1) and elsewhere well cells are only connected vertically to other well cells. This configuration simulates a perforated well section in the producing section of the target reservoir as the only exchange point for fluids between the well and its surroundings. We use a relatively low well permeability to reduce the computational cost of each simulation; a necessity for the number of models used in this work. This permeability assumption does not affect our analysis because we measure the gas production rate at the perforated section of the well where gas enters from the reservoir, and not at the top of the well.

Our modelling workflow is illustrated in Figure 3.2. We fix the pressure and temperature conditions at the bottom, top and right boundaries of the model, and the well acts as the left boundary about which the model is radially symmetrical. The 2D simulations were initialised to regional thermal and hydrostatic equilibrium conditions using available data (Hunter et al., 2011; Lee and Collett, 2011, Figure 3.3). Initial model temperature varies linearly with depth from 2.5 °C to 4 °C, with temperature in unit D between 2.6 and 2.8 °C. Unit D pressure increases linearly with depth from 6.7 to 6.8 MPa, with solid hydrate at this temperature beginning dissociation at pressure between 3 to 4 MPa.

Table 3.1 *Numerical parameters of different layers used in our model.*

Parameter		Value	Reference
Rock grain density (kg/m^3)		2700	*(Winters et al., 2011)*
Rock grain specific heat (J/kg/C)		1000	*(Anderson et al., 2011)*
Porosity	*Unit D*	0.4	*(Winters et al., 2011)*
	Unit C	0.35	*(Winters et al., 2011)*
	Other lithologies	0.3	*(Winters et al., 2011)*
Isotropic permeability (m^2)	*Unit D*	$1x10^{-12}$	*(Winters et al., 2011)*
	Unit C	$7x10^{-13}$	*(Winters et al., 2011)*
	Other lithologies	$5x10^{-14}$	*(Winters et al., 2011)*
Saturated heat conductivity	*Unit D*	2.20	*(Waite et al., 2009)*
(W/m/C)	*Unit C*	2.50	*(Waite et al., 2009)*
	Other lithologies	2.85	*(Waite et al., 2009)*
Relative permeability	$k_{rA} = max\left\{0, min\left\{\left[\frac{S_A - S_{irA}}{1 - S_{irA}}\right]^n, 1\right\}\right\}$ $k_{rG} = max\left\{0, min\left\{\left[\frac{S_G - S_{irG}}{1 - S_{irG}}\right]^{n_G}, 1\right\}\right\}$		*(Stone, 1970)*
S_{irA}		0.20	*(Moridis et al., 2011b)*
S_{irG}		0.02	*(Moridis et al., 2011b)*
n		4.50	*(Anderson et al., 2011)*
n_G		3.10	*(Anderson et al., 2011)*
Capillary pressure	$P_{cap} = -P_0\left[(S^*)^{-\frac{1}{\lambda}} - 1\right]^{1-\lambda}$, $S^* = \frac{(S_A - S_{irA})}{(S_{mxA} - S_{irA})}$ $-P_{max} \le P_{cap} \le 0$		*(van Genuchten, 1980)*
λ		0.77437	*(Moridis et al., 2011b)*
S_{irA}		0.3	*(Anderson et al., 2011)*
$1/P_0$		0.001	
P_{max} (pa)		$1x10^5$	
S_{mxA}		1	*(Moridis and Reagan, 2011)*

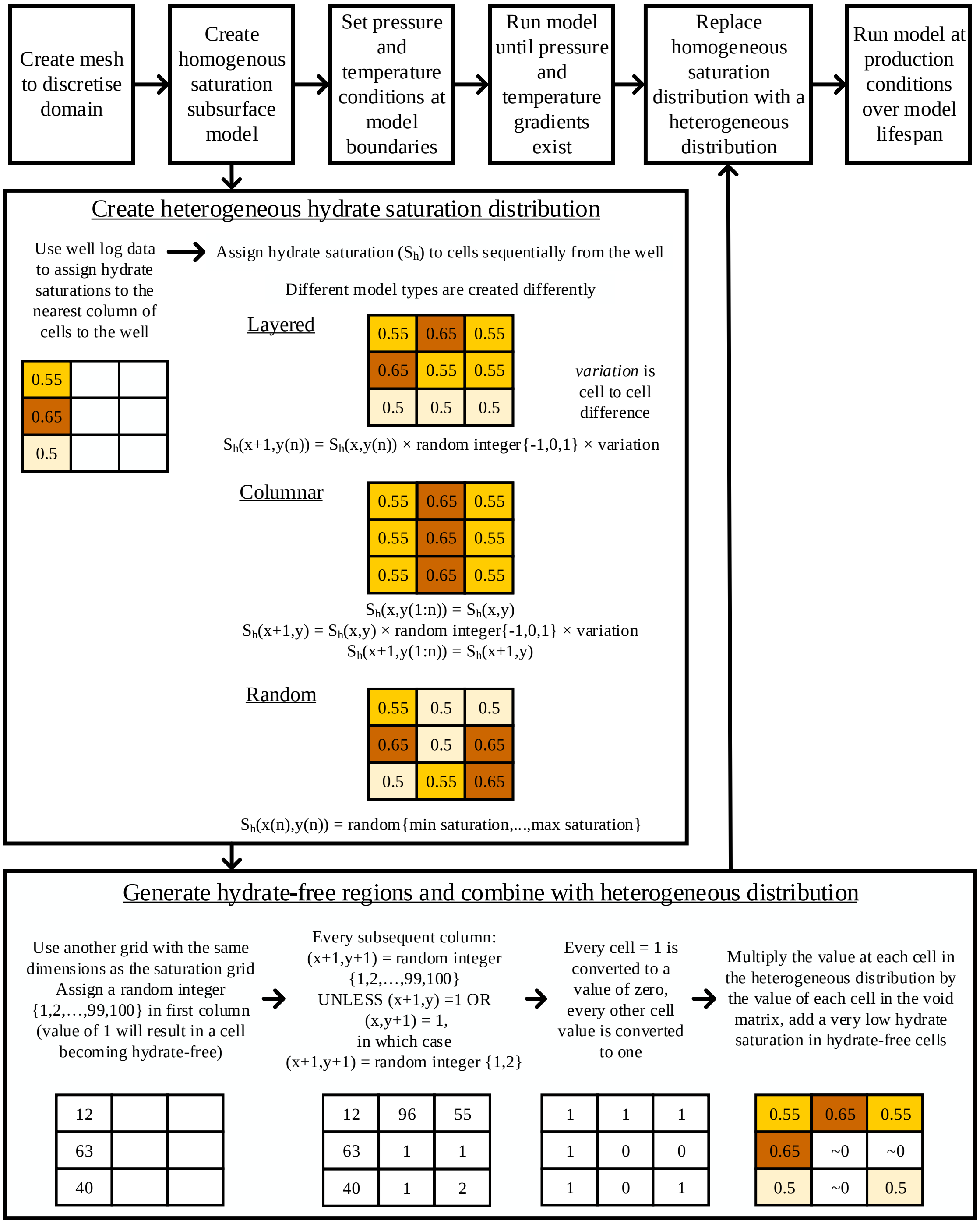

Figure 3.2 *Workflow illustration showing the main stages in model development and the methods used to generate different types of heterogeneous model.*

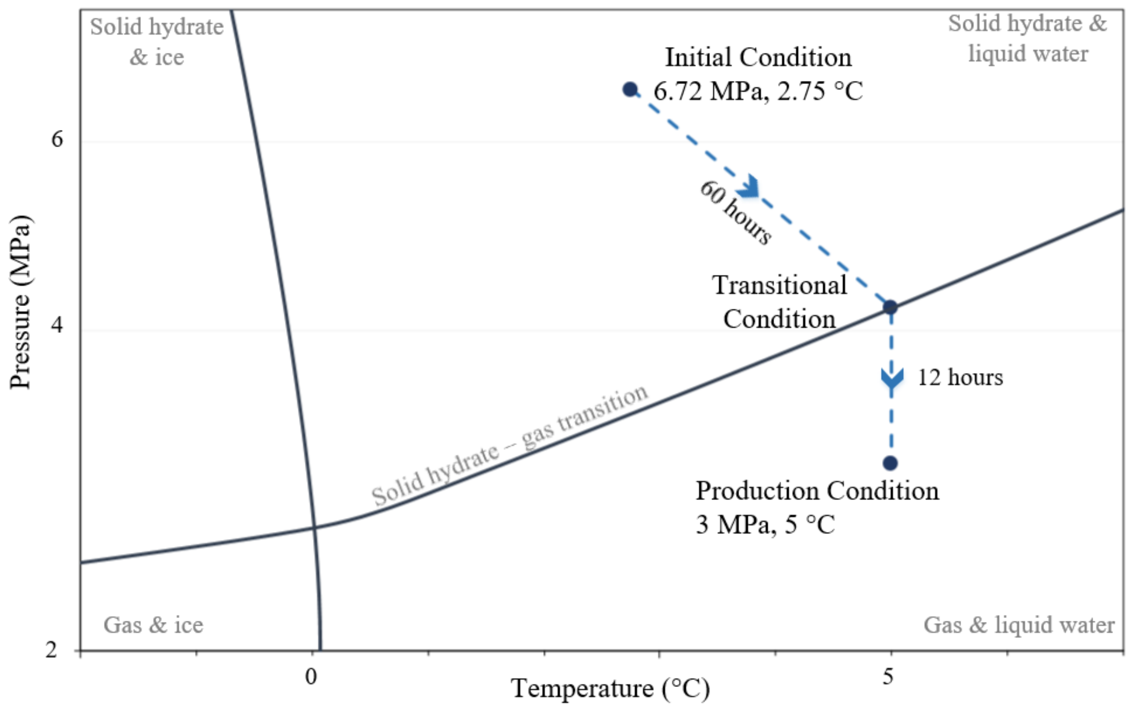

Figure 3.3 *Imposed change in pressure and temperature conditions from initial stable state to production at the well. Pressure axis is logarithmic. Hydrate production conditions were reached by first reducing pressure and increasing temperature over 60 hours (initial to transitional conditions), then by reducing pressure to the production pressure over 12 hours (transitional to production conditions), and finally by maintaining the temperature and pressure at production conditions for 30 years.*

We generated 34 heterogeneous models with three classes of hydrate distribution to explore changing this aspect affects gas production rate. Models are broadly classified as layered, columnar or random (Figure 3.4). The majority of the models used in our study were layered models (n=23, Figure 3.4a) as natural hydrate is most commonly distributed in layered formations (Cook et al., 2012; Lee and Collett, 2013). To generate layered models, the cells horizontally adjacent to the well margin in the hydrate bearing layers were assigned a hydrate saturation from well log data. For some layered models these saturations were continued unchanged radially across the entire hydrate bearing layer, generating models with constant saturation hydrate layers. In other layered models, saturation in each cell was varied following a random walk from their near-well neighbour cell where the saturation of each subsequent cell in the same layer either increases or decreases by a given amount or stays the same, creating layered models with variation along rows in the radial direction (Figure 3.2). The variation in the random walk between horizontally neighbouring cells was set at a constant value of 2.5% or 10% in individual models, to generate models with different degrees of heterogeneity.

We generated fewer columnar and random models as the natural hydrate distributions that these represent are less common in nature than layered formations. Columnar models may represent gas hydrate forming around vertical fluid escape structures (e.g. Lüdmann and Wong, 2003). In columnar models (n=6, Figure 3.4b), hydrate saturations were allocated to entire columns of cells in each hydrate layer. Values for column saturations were either chosen randomly from the known well log saturation values, or alternatively the well adjacent column was allocated a saturation of 55% and each subsequent column randomly increased or decreased in saturation by 2% or stayed at the same saturation as their near well neighbour column. Random models may represent biogenic hydrate generation, from within the hydrate bearing layer. In fully random models (n=5, Figure 3.4c) the hydrate saturation of each cell in the hydrate bearing layers was allocated a random saturation from a continuous sample space with a constrained maximum (75%) and minimum (25%) saturation. To add further heterogeneity to all models, hydrate-free regions were seeded in the hydrate bearing layers. Hydrate-free regions were seeded randomly from the well outwards with each individual cell given a 1% chance of being made hydrate-free, unless the near-well neighbour to a cell was a hydrate-free cell as this increased the chance of a cell being randomly seeded as hydrate-free to 50%. This approach created connected hydrate-free regions that represent areas where hydrate may not have formed due to local structural or compositional variations. All models are listed in Appendix A.

We stimulated hydrate dissociation using depressurisation from a single vertical well. Depressurisation is chosen as the production mechanism as it is seen as the most likely commercial hydrate production method (Demirbas, 2010; Li et al., 2010). We impose a constant bottom-hole pressure of 3 MPa in the connected well section (Figure 3.1). To reach this pressure we use a two stage pressure drop, initially dropping pressure to the pressure at which dissociation is about to commence, then dropping pressure to the 3 MPa final condition (Figure 3.3). This well pressure destabilises solid hydrate under the thermodynamic conditions of our model system, but it is not below the quadruple point pressure, limiting ice formation in the system. Similar to previous modelling studies on depressurisation-induced, hydrate-source gas production at Mt Elbert (Moridis et al., 2011b), we imposed a temperature of 5 °C in the connected well section throughout production to promote hydrate dissociation and to counteract partially the endothermic nature of the dissociation process. Our target reservoir at Mt Elbert is only 2–3 °C pre-production (Lee and Collett, 2011), meaning heat input is necessary to continue hydrate dissociation, maintain gas flow and prevent ice blockages developing at the interface between the well and the reservoir. The imposed pressure and temperature conditions for production are only fixed in the 5 m well section connected to the formation. Our production scenario was maintained for 30 years to simulate the operational lifespan of a typical gas well. Gas production rate was measured by gas flow into the well. Although also present in the model, unit C was not actively targeted for depressurisation.

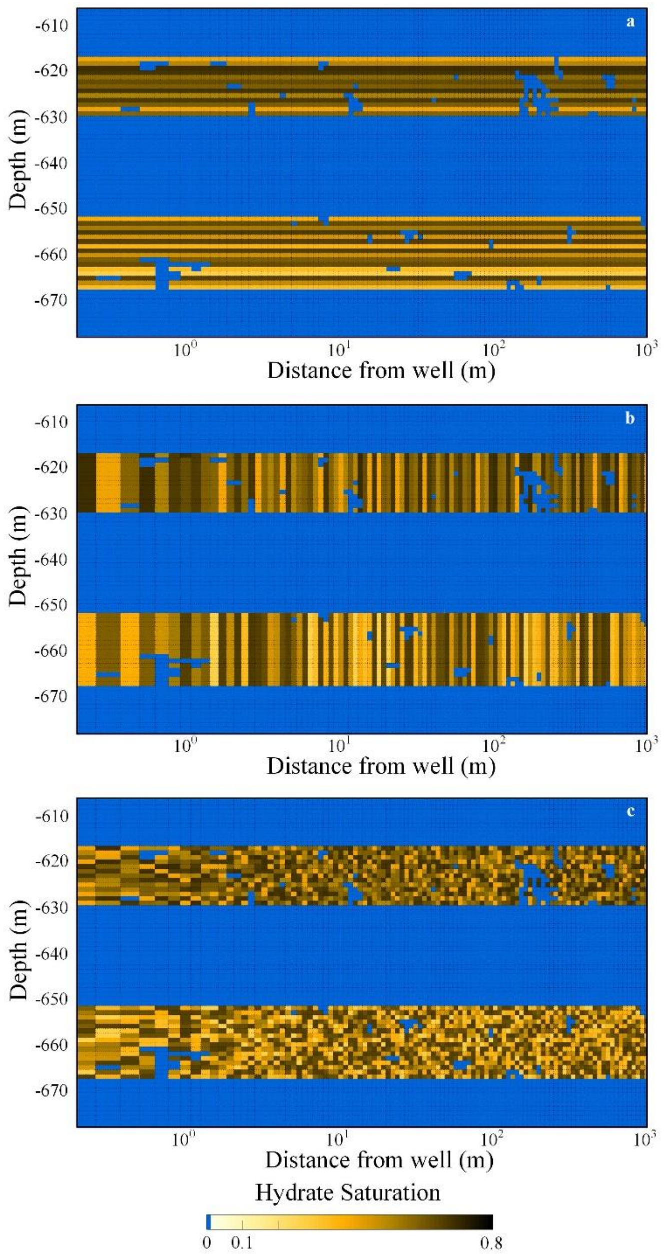

Figure 3.4 *Examples of (a) layered, (b) columnar, and (c) random models of hydrate saturation. Models are in initial state prior to any depressurisation taking place. These models also show connected hydrate-free regions as irregular areas of zero hydrate saturation within the hydrate bearing layers. In all models the locations of hydrate-free regions were varied. Horizontal scale is logarithmic.*

We quantified each heterogeneous saturation distribution using a series of summary statistics including the arithmetic mean hydrate saturation, a weighted mean, and a weighted mean considering only the closest half of the model to the well. We applied weighting schemes to the mean to assign less weight to hydrate further from the well and more weight to hydrate that will potentially dissociate. Since we are modelling the effect of heterogeneous hydrate saturation on gas production only material that dissociates or is between dissociating material and the well will influenced the measured gas production at the well. We tested for correlation and potential causation using the Pearson correlation coefficient between each summary statistic and gas production rate at 5 year intervals.

3.3 Results

We ran 34 heterogeneous models, of which 23 had a layered hydrate configuration, 6 had a columnar hydrate configuration and 5 had a random hydrate configuration and 3 homogeneous hydrate saturation models. All model configurations show similar time evolution of gas production rate (Figure 3.5). Gas production rate was normalised to the homogeneous 55% hydrate saturation profile to illustrate deviation from this profile. The initial rate of gas production is an instantaneous maximum, double or triple the standard rate of production in most cases, with variation across all models of ±35% from the homogeneous 55% hydrate saturation model. The initial high rate of production declines by two thirds within the next five years, after which production rate remains between 0.001 and 0.002 standard cubic metres per second (Sm^3/s) for all models throughout. In the homogeneous models gas production was highest with 60% hydrate saturation and lowest with 50% hydrate saturation (Figure 3.5). Gas production rate from heterogeneous distributions varies by up to 25% from the homogeneous distribution after the first five years until the end of our simulation (Figure 3.5). After dropping initially, production rate increases again to a second peak. In all cases a second maximum rate of gas production occurs between 8 to 11 years after production begins (Figure 3.6). After this second peak, production rate in all scenarios gradual declines towards long-term values of about 0.001 Sm^3/s. Our production rates are similar to those observed for other modelling studies in the same area (e.g. Moridis et al., 2011b). Heterogeneous production scenarios on average produce less gas than the homogeneous baseline (Figure 3.7). The largest variation in gas production rate outside the first year across all models occurs at the same time as the secondary peak in production rate, although this maximum variation is only caused by the behaviour of model 11 (Figure 3.7). If this model is excluded, the relative difference in gas production rate between all models remains at about 15% from 5 years to the end of production (Figure 3.5). The time evolution of gas production rate shows the balance between the expansion of the depressurisation front and the increasing distance that the produced gas has to migrate to reach the well. Initial high production rate is caused by dissociation of hydrate directly adjacent to the connected well section, as gas generated can immediately enter the well. This initial stage is where the highest spread in gas production rate is observed, as gas production is only dependent on the cells immediately adjacent to the perforated well section, and the mean saturation for this region can be substantially different between models. A second production rate peak occurs at the optimum balance between expansion of the depressurisation front, increasing hydrate dissociation, and increasing distance for produced gas to migrate to the well.

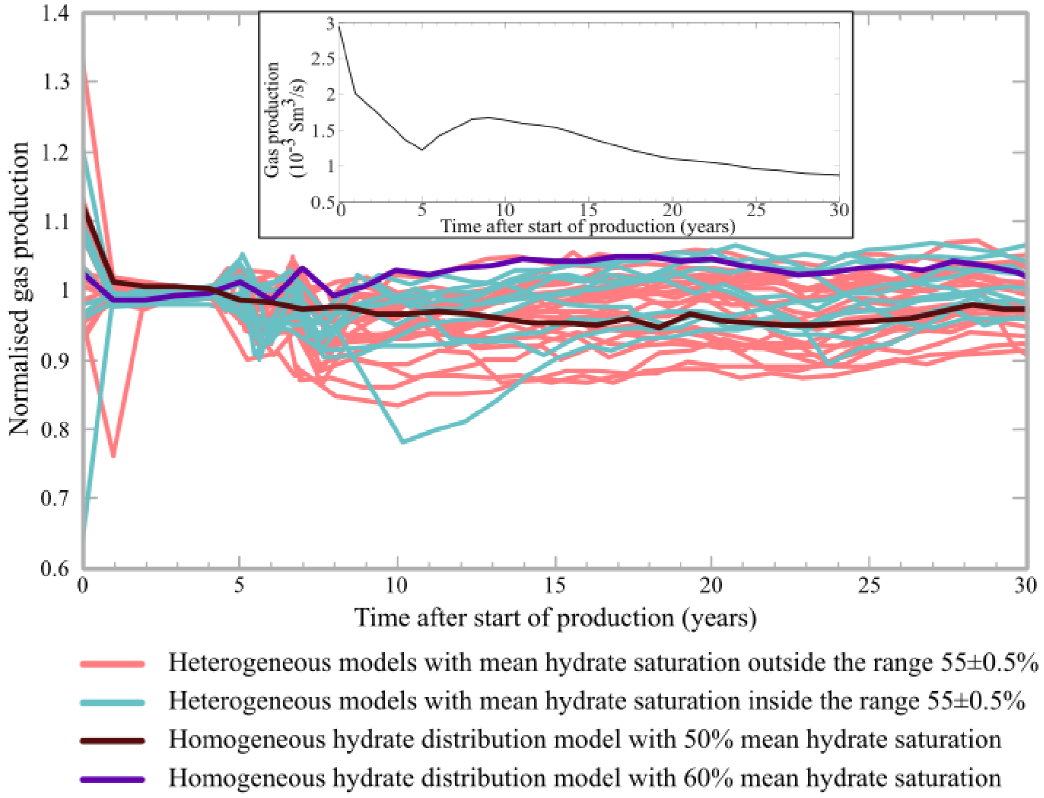

Figure 3.5 *Time evolution of gas production rate at the perforated section of the well for all models normalised to the gas production rate for the homogenous 55% hydrate saturation model (inset).*

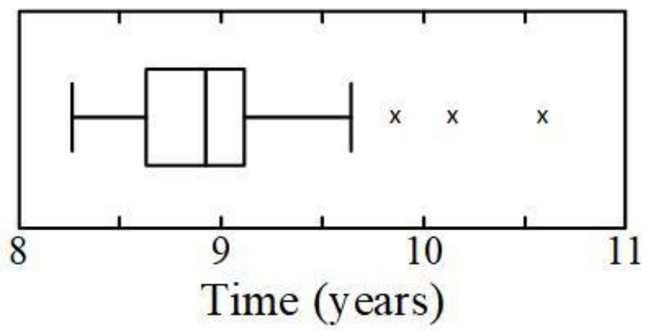

Figure 3.6 *Boxplot of lag time to second production peak across all models. Crosses show outliers, where the time is more than 1.5 times the interquartile range above the upper quartile.*

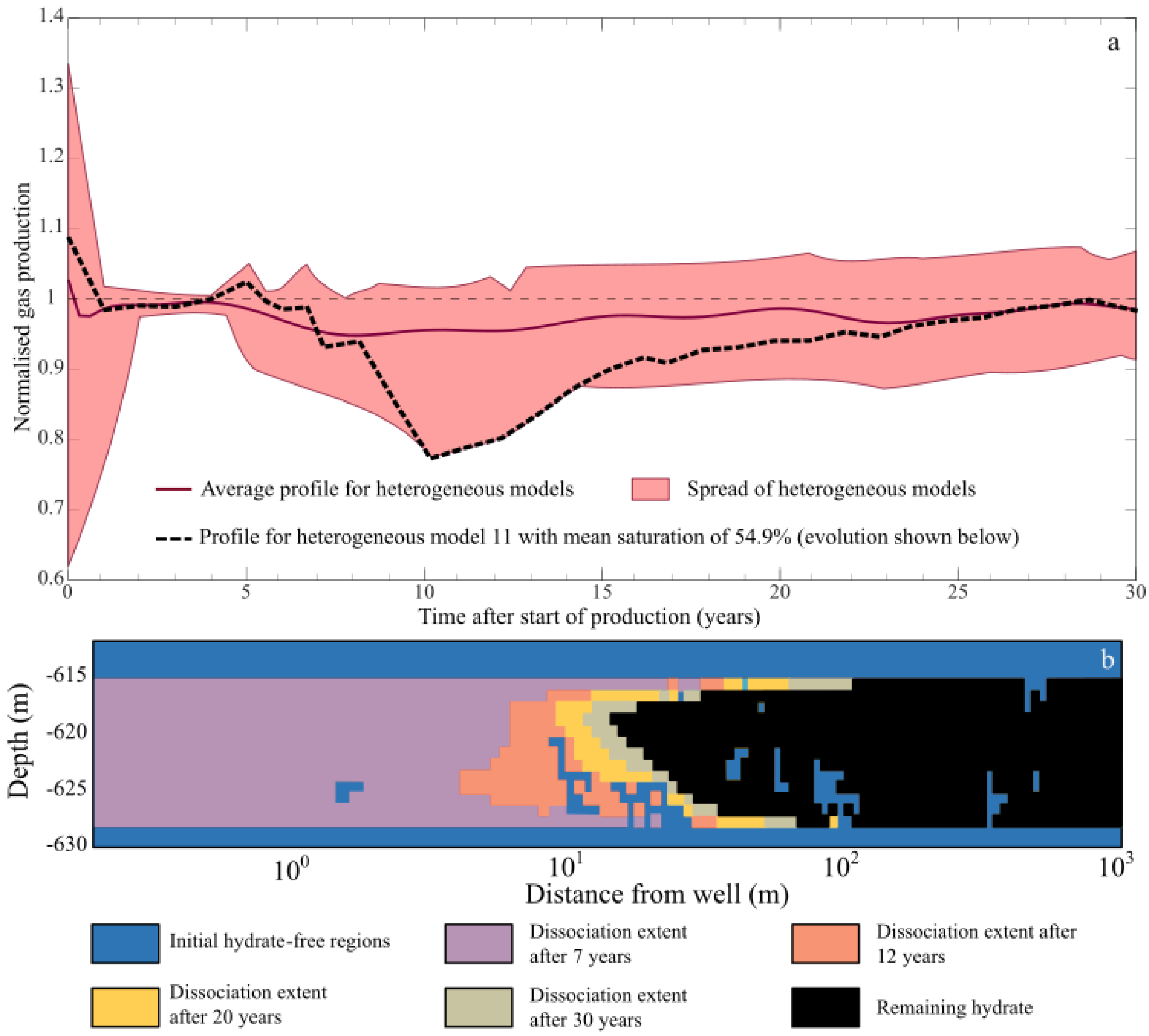

Figure 3.7 *(a) Time evolution of gas production rate at the perforated well section for all heterogeneous hydrate distribution models, normalised to the homogeneous 55% hydrate saturation model. (b) Time evolution of hydrate bearing unit D in heterogeneous model 11 with a mean hydrate saturation of 54.9% over the full production run. Colours indicate new hydrate-free regions at the time indicated, and remaining hydrate after 30 years of production.*

The overall pattern of gas production rate is very similar irrespective of the hydrate saturation distribution (Figure 3.8). Layered models exhibit higher variation in production rate than other distributions due to the higher number of layered models (n=23) compared to columnar (n=6) and random (n=5) models. Random models show gas production rate consistently ≤10% lower than the other two hydrate saturation distributions primarily because random models contain less hydrate on average (mean hydrate saturation in random models = 46.8%) than other models (mean hydrate saturation in all heterogeneous models = 52.0%,)

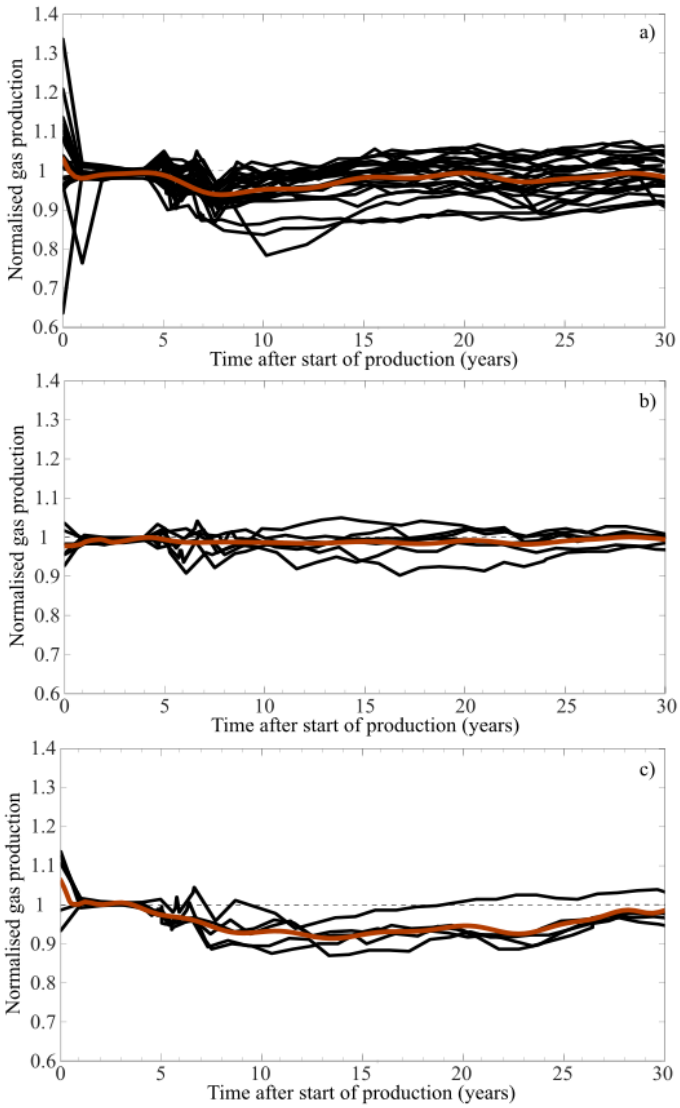

Figure 3.8 *Individually plotted gas production profiles at the perforated section of the well in each heterogeneous a) layered, b) columnar and c) random hydrate distribution model normalised to the homogeneous 55% hydrate saturation model. Red lines show the average gas production rate profile for each model class.*

In all models at the end of gas production the dissociation front in unit D has a convex shape resulting from preferential hydrate loss at the top and base of the layer (Figure 3.7b), as this is where heat flux from the surrounding material is the largest (Pooladi-Darvish and Hong, 2011). After 10 years hydrate fully dissociates from the closest ≈10 m to the well, and by the end of 30 years full hydrate dissociation occurs from the next ≈10 m, although the dissociation front extends further radially at the base and especially at the top of unit D, where for some models dissociation occurs across the entire model. The total penetration depth of the dissociation front and distance is closely similar for all models. This indicates that in our models penetration depth of dissociation is primarily controlled by the depressurisation conditions, and is mostly independent of hydrate saturation.

There is a moderate positive correlation between initial mean hydrate saturation and gas production rate throughout, ($0.5< r <0.67$, $p<0.005$, Figure 3.7), with the strongest correlation at 15 and 20 years ($0.66< r <0.69$, $p<0.005$, Figure 3.7). Moderate to high positive correlations between mean saturation and gas production rate indicate that increasing the amount of hydrate in the system increases gas production rate. More hydrate available to dissociate contains a greater volume of trapped gas, which can be released to give a higher production rate over time. When separated by configuration, layered models show similar correlation strengths in a similar pattern to the overall trend (Figure 3.9), indicating that layered models dominate the overall correlations as they comprise a significant proportion of the overall total of models. The correlations calculated for columnar models alone are not significant ($P>0.005$) due to the small number of columnar models. At some times the correlation for random models is significant, but the same general trend is observed for random models as layered and there are significantly fewer random models so these contribute less than the layered models to the overall trend. The weighting scheme increases the strength of correlation ($0.53< r <0.78$, $p<0.005$, Figure 3.9). In an attempt to further improve the correlation, and using the fact that penetration depth is similar across all models, we also applied a weighting only using the closest half of the model to the well, as this region approximately encompasses the part of the model which experiences hydrate dissociation due to depressurisation. The result of this second weighting scheme gives a slight further increase to the strength of the correlation ($0.53< r <0.82$, $p<0.005$, Figure 3.9). This correlation does not consider the contributions to gas production that occur from outside the closest half of the model to the well, especially within the last ten years of production. All correlation summary statistics are presented in Appendix A.

3.4 Discussion

The number of models and their degrees of variation in hydrate mean saturation and distribution are sufficient to identify, but not precisely quantify, impacts from these two parameters independently, as we varied hydrate mean saturation and distribution in our heterogeneous hydrate models concurrently. For further analysis we have divided the total range of models into classes based upon the difference between model hydrate mean saturation and the 55% mean hydrate saturation used in our initial homogenous model. In this way we isolate the impact from hydrate distribution by considering differences in production for all models with similar mean hydrate saturations. By separating the models based upon their mean hydrate saturation, reliable moderate to high correlations between initial means and gas production rates only emerge at all times when reaching variations in saturation of ±11% from the homogenous distribution (Figure 3.9e, f). This observation suggests that mean hydrate saturation is not the only influence on gas production rate, and is only the primary influence when total hydrate saturation differs significantly between models. For all other groups and times we obtain low or non-significant correlations (Figure 3.9e, f), likely suggesting that system heterogeneity is causing the observed variations in gas production rate. Sampling all of the heterogeneous production scenarios with mean hydrate saturations of 55±0.5% irrespective of model type (layered, columnar and homogeneous) shows that the scale of variation in gas production rate is larger than between homogeneous distributions with saturations of 55±5% (Figure 3.5). This result suggests that large local differences in hydrate saturation, which are masked when considering the volume as a whole, can generate significant variations in gas production rate. Therefore, using a range of homogeneous distributions to estimate error may not be sufficient to encompass the variation in gas production rate resulting from natural hydrate distribution heterogeneity.

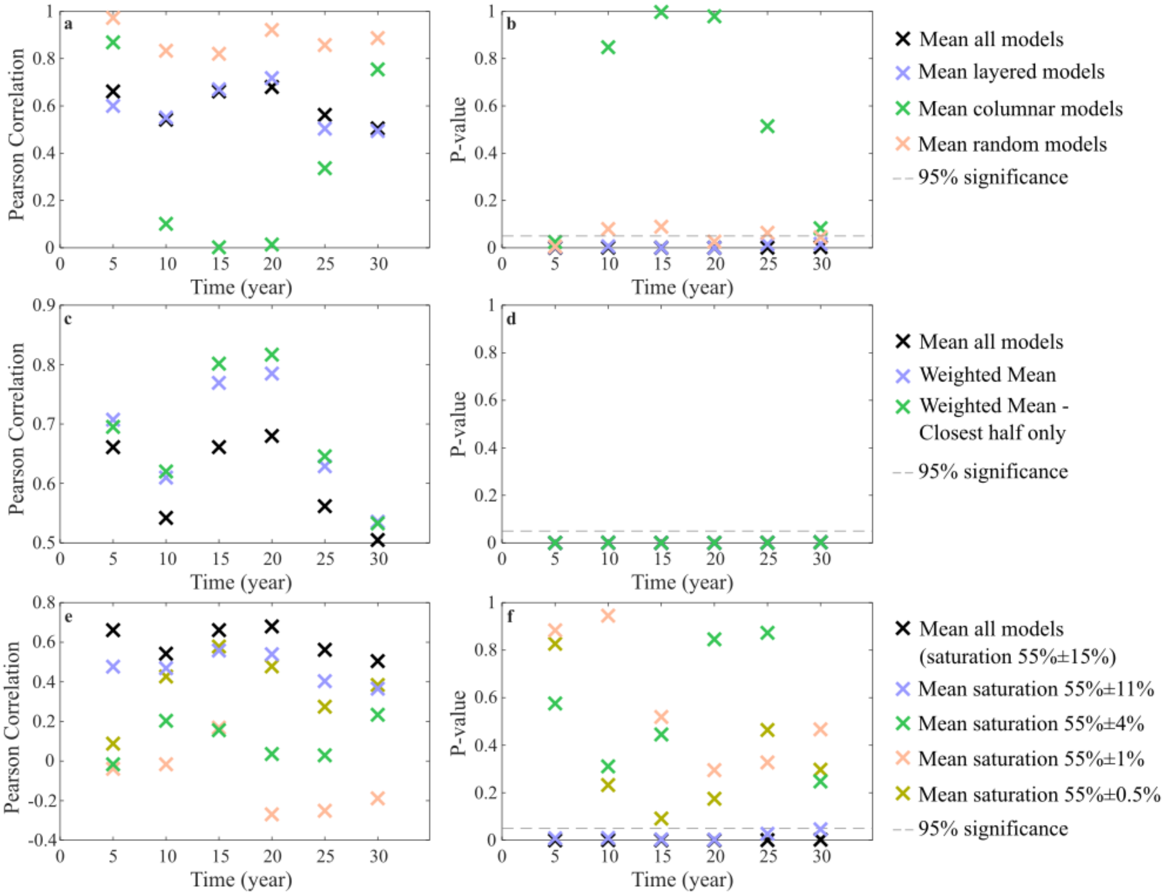

Figure 3.9 *Correlation and confidence values between different estimates of mean hydrate saturation and gas production rate at the perforated section of the well for different model samples. (a) Correlation and (b) confidence values between mean hydrate saturation and gas production rate for the three classes of heterogeneous hydrate distribution models considered. (c) Correlation and (d) confidence values between different estimations of mean hydrate saturation and gas production rate for all heterogeneous hydrate distribution models. (e) Correlation and (f) confidence values between mean hydrate saturation and gas production rate for all heterogeneous hydrate distribution models, grouped into five different sampling sets. In (c) symbols plot on top of each other.*

The lag between production initialisation and peak production rate as identified before (e.g. Anderson et al., 2011), is likely caused by the high water production in hydrate dissociation. Excess water must be removed before gas is produced and also requires free gas in the system to build until it becomes a mobile phase (Walsh et al., 2009). The lag to maximum production has been shown to be mesh dependent (Boswell et al., 2017a), but this factor will influence the overall lag times exhibited by all models, and cannot explain the differences in lag times shown in this study between models using the same mesh. In our models, differences in hydrate saturation cause variations in free water content, liquid and gas permeabilities, sediment thermal conductivity, and the volume of water produced from hydrate dissociation. The combination of these factors causes the variability in lag times between our models (Figure 3.6). Over time the propagation rate of the dissociation front in the radial direction decreases as a lower absolute pressure decrease due to depressurisation at the well is experienced at greater distances from the well. Additionally, the produced gas has to migrate further over time to reach the wellbore. Both factors result in a gradual decline in gas production rate in all models after the first 10 years of production. In a commercial development several production wells may be used with a well spacing lower than the 1 km radial distance of our model (Wilson et al., 2011). Closer well spacing would reduce the migration distance for any produced gas and also contribute to pressure reduction, if depressurisation is applied at different production wells, reducing the decay in gas production over time. By imposing constant depressurisation conditions we do not include the impact of suspensions in depressurisation that would necessarily occur in production and may cause hydrate reformation. However, the focus of our work is comparing dissociation in different hydrate deposits and not attempting to optimise production approaches.

The layers above and below unit D are not modelled here as totally impermeable as assumed in some prior modelling studies (Chejara et al., 2013). We observe that depressurisation propagates into the lower hydrate bearing layer, unit C, causing gas production at the top of unit C, despite our model not directly targeting the layer for production. Gas produced from unit C has to migrate slowly through the lower permeability material between the two hydrate bearing layers before it contributes to production. This contribution begins ≈10 years after production starts. Before this time pressure driven gas flow dominates over buoyancy driven flow and so some gas generated from unit D is driven by pressure into the layer beneath, between units C and D. Gas saturations in the material between the two hydrate bearing layers, with gas contributed from both hydrate bearing layers, reach 10% after 30 years (Figure 3.10). The contribution of non-targeted units is an important consideration when producing hydrate from layered formations. Also, the permeable overburden does not perfectly seal the system, resulting in a fraction of produced gas entering the overburden and not contributing to production. There is no ready pathway for gas escape from the overburden, so gas saturations can reach 15% compared to 5-10% in the hydrate bearing layer. The permeability of the overburden is especially significant as hydrate dissociation propagates preferentially along the top surface of unit D, from where produced gas can immediately enter the overburden. In commercial production the fluid connected region of the well to the formation may need expansion into the overburden to capture this escaped gas.

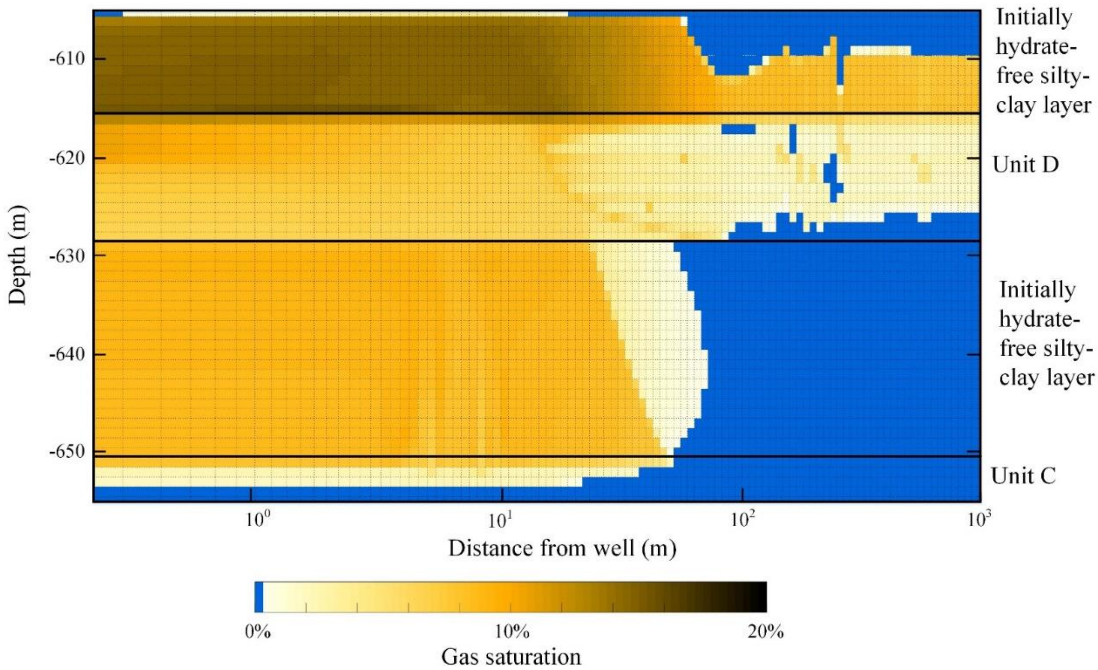

Figure 3.10 *Gas saturation in the layered hydrate model shown in Figure 3.4a after 30 years of production.*

When the dissociation front encounters a hydrate-free region, the deficiency leads to a drop in gas production rate while the hydrate-free region forms part of the active system. The hydrate-free region may promote dissociation further from the well as the pressure wave propagates more easily in the hydrate-free region. In this case however, increasing the range of dissociation does not necessarily increase gas production rate, as gas produced from additionally affected hydrate has further distance to migrate to reach the well. Heterogeneous model 11 (Figure 3.7) shows effects of both mean hydrate saturation and hydrate distribution. Heterogeneous model 11 is a layered model with a mean saturation (54.9%) that is close to the mean saturation of the initial homogeneous model (55%) but hydrate distribution, and specifically the presence of a large hydrate-free region in the active zone of the hydrate-bearing layer caused a 5 year period where gas production rate is 15% below the average production profile for heterogeneous models (Figure 3.7a). Before the dissociation front reached this hydrate-free region, and once dissociation has passed this hydrate-free region, gas production rate has a normalised value of 1 (Figure 3.7a), indicating a gas production rate near-identical to that of the homogeneous model with near-identical hydrate saturation. The hydrate-bearing layer of our studied system has a very high permeability (10^{-12} m^2), allowing the migration of produced gas to the well to outpace the propagation rate of the dissociation front, and lowering the chance for secondary hydrate reformation. As such, the production rate is mainly controlled by the presence or absence of hydrate at the dissociation front at any given time. Accordingly, regions with significant saturation variation in similar natural systems can cause multi-year periods of irregular gas production rates compared to expected estimates from equivalent homogeneous models.

Gas flow in our model generates pathways preferentially avoiding high hydrate saturation regions which have relatively low permeability. The overall high permeability of our modelled hydrate-bearing layer allows ready creation of fluid pathways around any high hydrate saturation regions acting as temporary barriers. This can lead to isolated regions without gas within the hydrate bearing layer as a result of local high hydrate saturation conditions (Figure 3.10 and Figure 3.11). Due to preferential hydrate dissociation along the top surface of unit D, gas is present across the width of the model, but not through the entire depth of the hydrate layer. In Figure 3.11a gas generated at the top of unit D has travelled down to a hydrate-free region within the layer, and then preferentially towards the well using the low hydrate saturation layers at the top of unit D and at 620 m depth, avoiding high hydrate saturation regions. By contrast, in Figure 3.11b a series of high hydrate saturation layers provides a more effective barrier to gas flow that also explains the lower gas production rate in heterogeneous model 11 over the period 10-15 years after gas production begins. Compared to the model in Figure 3.11a, gas generated at the top of unit D has to migrate deeper into unit D before it finds a lower saturation pathway at 622 m to migrate to the well. Figure 3.11b also shows the impact of radial variation of hydrate saturation within a broadly layered model, as gas follows the layer at 620 m depth, until increasing hydrate saturation decreases permeability sufficiently to hinder gas flow. In layered hydrate distributions, low hydrate saturation layers provide pathways for lateral flow of gas until a radial change in hydrate saturation occurs. The hydrate-free regions in our domain provide routes for gas to transfer between layers as gas seeks the highest permeability pathway available. Therefore, the path taken for generated gas to reach the well is likely more tortuous the more irregular the hydrate distribution is. Real-world formations also have heterogeneity in a third dimension not represented in our model further complicating the available pathways for gas flow.

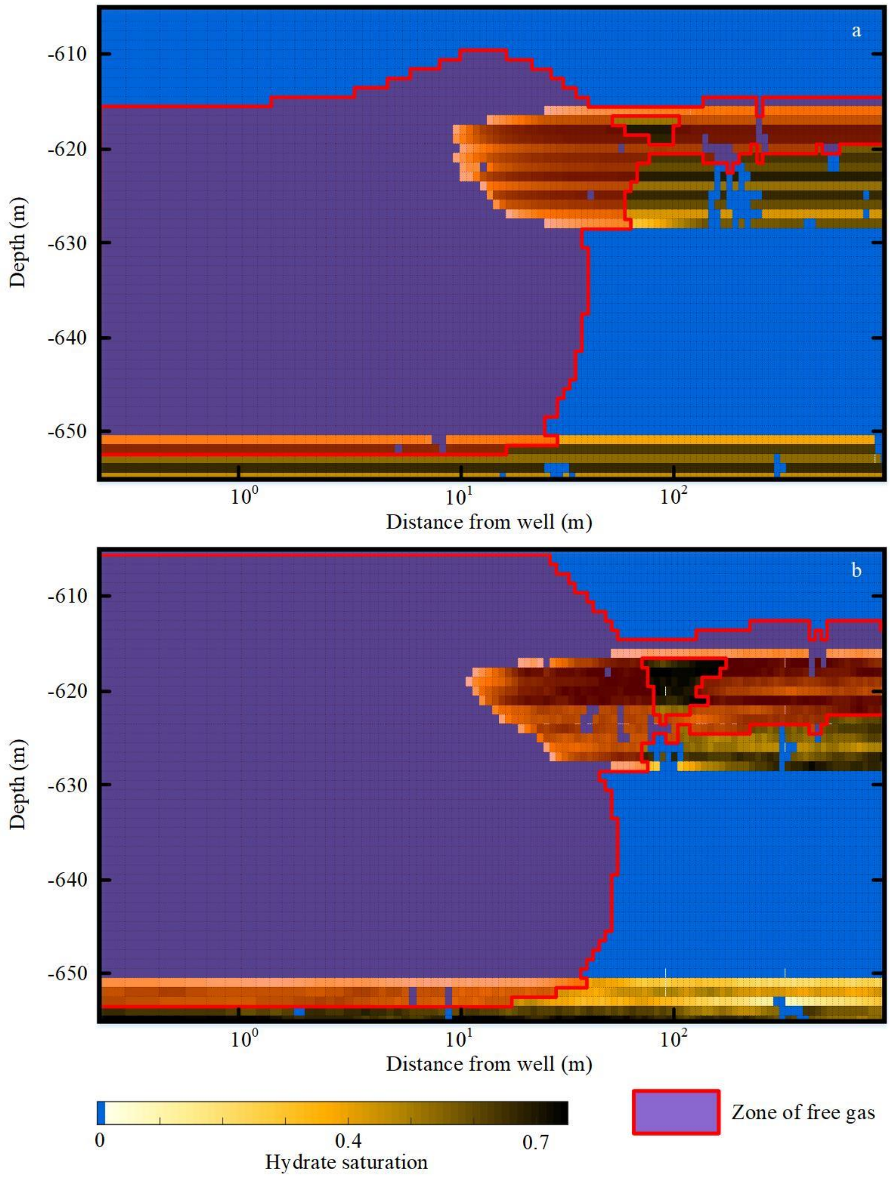

Figure 3.11 *Hydrate and gas saturations for (a) the layered model shown in Figure 3.4a after 11 years of production and (b) the heterogeneous layered model 11 (gas production rate profile shown in Figure 3.7a) after 11 years of production*.

Independent validation of our results would be provided by using a geologically equivalent laboratory sample to our modelled reservoir, creating different distributions of synthetic hydrate in this material, then measuring gas generation for imposed dissociation on these hydrate distributions. Further modelling could establish if our conclusions hold when modelling dissociation in other hydrate reservoirs.

3.5 Conclusions

We have used the Mt Elbert site to generate heterogeneous distributions of gas hydrate and assess their impacts on gas migration through the system and gas production rate with respect to homogeneous distributions. The conclusions of our analysis are as follows:

- The general evolution over time of the production profile is similar irrespective of the hydrate distribution but gas production rate can vary by up to ±40% during the first year of production and by up to ±20% over the remaining production lifespan.
- Differences in mean hydrate saturation between models heavily influence gas production rate in active systems when differences in mean hydrate saturation between modelled systems exceed 10%.
- For differences in mean hydrate saturation below 10%, hydrate distribution likely dominates gas production rate variation as the scale of variation in gas production rate between models is larger in models with heterogeneous distributions of hydrate than with homogenous distributions for the same hydrate saturation range.
- In high permeability systems the instantaneous gas production rate is primarily affected by the amount of hydrate at the dissociation front, suggesting that gas production in these systems has little memory of the propagation history of the dissociation front.
- Highly heterogeneous distributions of hydrate, including hydrate-free regions, likely generate a more tortuous migration pathway of generated gas to the well.
- Local large variations in hydrate saturation, such as hydrate-free regions, can be unnoticed when characterizing the whole hydrate layer, particularly when the hydrate-free region is beyond the immediate vicinity of the production well, but can affect gas flow in the formation and production rate for multiple years.
- Heterogeneity in hydrate saturation, results in uncertainty that must be accounted for when attempting to predict gas production from real world gas hydrate deposits.

Chapter 4 A Social, Environmental and Economic Evaluation Protocol for Potential Gas Hydrate Exploitation Projects

This chapter has been published as:

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There is increasing global interest in the potential commercial development of methane gas hydrate as a widespread and abundant unconventional source of natural gas. Previous work has focussed on understanding the nature and distribution of the resource, and potential recovery technology, neglecting assessment of the associated social, economic and environmental consequences. This gap needs to be addressed for any commercial gas hydrate development business case to succeed. Here we develop a multi-criteria decision analysis (MCDA) protocol of gas hydrate development using the ELECTRE III method. Our protocol proposes criteria that evaluate the social, environmental and economic impacts of gas hydrate development proposals, which are weighted to represent the priorities of six identified stakeholder groups. We have tested the protocol on potential commercial gas hydrate development in Alaska through a series of interviews. Our results show that there is no universal preference structure, even within stakeholder groups, indicating that buy-in from all groups is a complex compromise. However, there are two fundamentally opposing groups, one composed of individuals from governmental and industry backgrounds who prioritise economic criteria, and another represented by members of the local community and environmental advocates who prioritise social and environmental criteria. The protocol concludes that gas hydrate development in Alaska is unlikely to be supported under present-day conditions. This work provides the first structured foundation for comprehensive assessment of future development proposals of gas hydrate or other natural resources.

4.1 Introduction

Natural gas is projected to see increasing use in future energy supply as a cheap, accessible fuel source, and remain an integral part of global energy infrastructure for decades (IEA, 2018). Environmental considerations form a major motivation for further use of natural gas, as gas has lower emissions per unit energy than other carbon based fossil fuels (Chong et al., 2016). As a result, natural gas is projected to replace coal in future energy generation to help meet emission targets (Chong et al., 2016). Increasing demand has motivated research and commercialisation of unconventional sources of natural gas, such as shale gas, and interest remains in broadening the gas supply base (Vedachalam et al., 2015). Gas hydrates are naturally occurring, solid, crystalline compounds containing molecules of a gas, most commonly methane, in a lattice cage of ice (Sloan and Koh, 2007). Estimates differ on the precise volume of gas hydrate present in permafrost and marine shelf regions worldwide, but it is generally accepted that total volumes of gas in gas hydrate are comparable to gas in conventional gas resources (Collett et al., 2015; Koh and Sloan, 2007). Since large volumes of natural gas can be liberated from gas hydrate, it has the potential to be a significant unconventional source of natural gas (Boswell and Collett, 2011; Demirbas et al., 2016). Many countries with significant gas hydrate reserves lack substantial conventional resources within their jurisdiction, so development of gas hydrate could provide these nations with a domestic resource that lessens their reliance on foreign imports (Oyama and Masutani, 2017).

Geological surveying (e.g. Tsuji et al., 2004), laboratory studies (e.g. Li et al., 2016; Sum et al., 2009), numerical simulation (e.g. Anderson et al., 2011; Sun et al., 2014) and field testing (e.g. Li et al., 2016; Moridis et al., 2009) have all been undertaken with the end goal of achieving commercial gas production from gas hydrate. Field production tests have occurred at the Messoyakha gas field in central Russia (Makogon and Omelchenko, 2013), the Alaskan North Slope (Hunter et al., 2011), the Canadian Mackenzie Delta (Kurihara et al., 2010), offshore Japan in the Nankai Trough (Konno et al., 2017; Oyama and Masutani, 2017) and offshore China in the South China Sea (Li et al., 2018), with all tests aiming to establish best practices for production, before large scale commercialisation happens. Field testing has shown that gas can be produced from gas hydrate using conventional well production technology (Collett et al., 2015). As this result establishes gas hydrate as a technically recoverable resource, further study is required to determine if it can be considered an economically recoverable resource (Boswell and Collett, 2011). Even if economic viability is achieved, understanding the wider social and environmental consequences of gas hydrate development is necessary to understand the future potential of the resource (Walsh et al., 2009).

Introducing commercial gas hydrate production development to a region, as with many other industrial developments, has far-reaching consequences. For commercialisation to occur soon, the broader impacts of gas hydrate exploitation need to be researched simultaneously with production technology and resource evaluation. Current analysis of the wider implications of developing gas hydrate (Tan et al., 2016; Zhao et al., 2017) has not been linked with detailed assessments of gas production. Present gas hydrate research is focussed on evaluating resource size at any specific location and the effectiveness of the chosen production technique, but investigation beyond the technical aspects of gas hydrate production is rare. Technical studies compare the efficiency of different production techniques (Zhao et al., 2015), but lack commercial economic data to establish the cost-effectiveness of each approach (Boswell and Collett, 2011). In some studies the economic case for commercial gas production is investigated once a gas production rate has been estimated (Marcelle-De Silva and Dawe, 2011), but this analysis is usually limited to attempting to establish a market price at which gas hydrate production may be economically viable. Determining a market price is complicated by the uncertain future of global markets, and the undetermined technological development pathway for gas hydrate (Max and Johnson, 2016). As a result, economic studies that have followed Arctic field tests, have used gas production and development costs to compare gas hydrate to other resources (Walsh et al., 2009). Although providing a useful estimate of economic viability, these estimates do not consider the cost and value of gas hydrate down the full industrial supply chain (Tan et al., 2016).

While preliminary economic work has begun, there are very few studies that investigate environmental and social impacts related to specific gas hydrate production projects. There is some understanding of environmental risks that may be encountered from gas hydrate production, especially the potential for uncontrolled large-scale release of natural gas into the atmosphere and the associated climatic effects (Moridis et al., 2011a). Commercial gas hydrate targets are not the same reservoirs that are most at risk of dissociating with a climatic impact (Boswell and Collett, 2011), so more research is needed to identify the environmental consequences of a commercial project. Environmental monitoring during field testing of gas hydrate production currently provides the best insight into possible adverse environmental impacts (Li et al., 2018). However, other possible social and environmental impacts from gas hydrate production have not been explored in such depth (Li et al., 2016). Unlike other studies, we consider environmental pollution throughout the gas hydrate supply chain to the end consumer. This comprehensive study of environmental impact will be necessary in any commercial gas hydrate development (Chong et al., 2016). National energy policy plays a large role in dictating which resources are developed, and gas hydrate projects have been motivated by national programs (Zhao et al., 2017). Research on policy controls on gas hydrate development currently focuses on environmental regulation only (Zhao et al., 2017), and does not consider other government actions that may promote or hinder development. Societal impacts, relevant to the public before a social license to operate can be achieved (Gehman et al., 2017), are yet to be considered with gas hydrate commercialisation. At present, the high level of uncertainty surrounding the impacts of gas hydrate commercialisation makes optimal resource development difficult to establish.

As different countries and organisations have different regulatory requirements, there is no universally accepted approach for combined social-environmental-economic evaluation of natural resource projects. Evaluation within industry generally takes the form of environmental impact assessments, and/or social impact assessments and/or health impact assessments (Gangolells et al., 2015). In most industrial applications the economic dimension is considered separately to these impact assessments. At present, health impact assessments are rarely a regulatory requirement (IPIECA, 2016) and often struggle to reach definitive results when attempted for unconventional projects due to the limited available data for newly created systems (Adgate et al., 2014; Werner et al., 2015). Within the International Association of Oil & Gas Producers, whose members include most major oil and gas development companies, the Environmental-Social-Health Risk and Impact Management Process (E-SHRIMP) is presented as the primary generic framework for identifying and managing the broad impacts of any project (Ord et al., 2007). This approach identifies the positive and negative impacts associated with achieving an objective, aiming to avoid or minimise negative impacts (Environmental Social & Health Impact Assessment Task Force, 2014). The E-SHRIMP is primarily concerned with mitigating the risks of a single project (Ord et al., 2007), whereas we seek to comparatively present the positive and negative impacts of multiple project proposals. Without a consensus method for holistic assessment of energy resource development, we generate a methodology for comprehensive assessment of gas hydrate development assessment in which economic, environmental and social impacts are considered together in the project proposal phase. This study presents the first attempt that we are aware of to evaluate the impact of commercial gas hydrate development on all these areas simultaneously. We aim to create a protocol that can be used by any decision makers who are comparing a range of different gas hydrate development proposals. The protocol aims to inform a decision maker by presenting a single assessment that comprehensively compares different gas hydrate development proposals, collating information from many sources.

In the next section we describe the possible impacts on the economic, social and environmental spheres from commercial production of gas from hydrate. We use these to suggest a structured protocol for evaluating different gas hydrate proposals. We have tested the protocol using potential development at the Alaska North Slope. Alaska was chosen from possible gas hydrate production sites to illustrate the protocol as there have been production tests at the North Slope and much of the data necessary to test the protocol is openly available (Hunter et al., 2011). This production testing makes Alaska likely to be one of the earliest locations where commercial gas hydrate production may occur onshore (Collett et al., 2012). Knowledge of the potential gas hydrate resource and its development is limited to a small portion of Alaskan society. By discussing with a range of stakeholders representing a cross section of Alaska, our study is one of the first attempting to present wider societal views on this development.

4.2 Protocol Development

4.2.1 Multi-Criteria Decision Analysis

Available techniques for decision aid divide into two primary schools based upon whether they are wholly monetary or not. A wholly monetary method, such as cost-benefit analysis (CBA), uses economic efficiency of resource distribution as the main method to appraise projects, aiming for optimum resource distribution (Boardman et al., 2017). CBA seeks objective decision making through comparison of total monetary cost to benefit, so is commonly used in commercial settings (Department for Communities and Local Government, 2009; Ikeda, 2011). Market valuations of impact used in economic analyses are generally considered very robust, as the value has been derived from the aggregation of many individuals' preferences (Pearce, 1983). Although relying on monetary valuation of all impacts, CBA is not limited solely to the financial dimension of a problem, as non-marketed social and environmental impacts are also included in monetary terms as much as possible (i.e. social cost-benefit analysis (Sidhu et al., 2018)), with the superior project providing greatest overall net benefit across all areas (Boardman et al., 2017). For more detail on the CBA approach see Boardman et al. (2017) and Saarikoski et al. (2016). When using an economic approach, the final benefit value can be compared between multiple studies for context, which can be used to justify the alternative choice. If a course of action is taken, the true net benefit can be compared to the calculated result, to identify discrepancies that can be taken into account in future appraisals. This accountability is one of the main advantages of commercial CBA use for policy decisions.

In contrast, other methods such as multi-criteria decision analysis (MCDA) seek to combine qualitative and quantitative information. MCDA also relies upon preferences elicited from stakeholders to aid a decision maker in reaching an informed conclusion (Belton and Stewart, 2002). Multi-criteria techniques are used for strategic development in optimisation problems where there are many different aspects to consider (Kumar et al., 2017). In addition, MCDA facilitates stakeholder engagement and group decision making in problems with many different stakeholder viewpoints (Huang et al., 2011). For more on MCDA see Olson (1996). There has been a growth in use of multi-criteria techniques in natural resource assessment in the past 30 years due to a shift in perception (Huang et al., 2011), as natural resource problems are now more commonly considered as requiring complex trade-offs between environmental, social and economic factors (Kiker et al., 2009). While there are no established protocols for assessing gas hydrate development as a multi-criteria problem, MCDA has been used for management and development of both sustainable and non-renewable energy resources (Huang et al., 2011; Kumar et al., 2017; Mardani et al., 2017). In particular, MCDA has seen significant use in environmental impact assessment (Herva and Roca, 2013).

Many criteria that are appropriate for gas hydrate assessment are difficult to assess in monetary terms due to infancy of the hydrate production industry, which limits available data. MCDA is regularly used in problems with both monetary and non-monetary elements (e.g. Chan et al., 2012; Martin and Mazzotta, 2018; Saarikoski et al., 2016). However, CBA relies upon transforming all elements to a consistent monetary unit (Boardman et al., 2017), which makes CBA unsuitable for our situation. Also, some fundamental assumptions in monetisation necessitate valuations of elements of ecosystem services or human lives that can be deemed controversial (Saarikoski et al., 2016). Although it may be possible to use indirect valuation methods to derive a value (Cellini and Kee, 2015), a lack of consensus on monetisation can make precise valuations difficult (Costanza et al., 2014). By not relying on monetary transformations to conduct an economic analysis, we broaden possible impact considerations to create a more comprehensive protocol. Some ecosystem services may have minimum acceptable values below which further loss would damage the ecosystem service in a manner which could not be compensated by gain in any other element (Fisher et al., 2008). This behaviour is difficult to include within CBA which allows trade-offs between all criteria, such that loss of value in one criterion can be compensated by gain of value in another (Wegner and Pascual, 2011). Moreover, trade-offs between different ecosystem services may be perceived differently by different stakeholders, who would have different values for the same trade-off relationship, especially where they deem two criteria incommensurable (Howe et al., 2014). Due to these limitations of CBA that are highly relevant to an evaluation of gas hydrate production, we choose an MCDA approach for our assessment protocol.

Specifically, we use an outranking MCDA approach (Mendoza and Martins, 2006). Outranking models compare each problem solution to other potential solutions, to establish which solutions are superior (Mendoza and Martins, 2006). Outranking methods enable the use of data in natural scales without requiring normalisation across all criteria, and this feature allows us to aggregate information from different fields within a single assessment (Figueira et al., 2013). Additionally, outranking models accommodate the use of imprecise data with high error margins, while still creating reliable comparison between alternatives (Figueira et al., 2016b). It may also be more appropriate to represent some imprecise data qualitatively, and outranking allows qualitative and quantitative data to be used in parallel (Figueira et al., 2016b).

4.2.2 ELECTRE III

The main outranking methods used in multi-criteria environmental problems are the ELECTRE (ELimination Et Choix Traduisant la REalité) family and PROMETHEE (Preference Ranking Organisation METHod for Enrichment of Evaluations) (Huang et al., 2011; Kangas et al., 2001). PROMETHEE requires stakeholders to define their preference between alternatives by selecting from a series of preference functions and then defining whatever points are required to complete their chosen preference function (Behzadian et al., 2010). This approach places high technical expectations on the stakeholders that may limit their participation. Therefore, we use an ELECTRE approach in this study. ELECTRE has been customised for different applications, creating a family of methods, of which ELECTRE III is the most commonly used (Govindan and Jepsen, 2016). ELECTRE III is an adjustment of ELECTRE to use imprecise data (Zanakis et al., 1998), which is especially necessary in the period before any long term gas hydrate exploitation has occurred. ELECTRE is non-compensatory, whereby very poor performance against one criteria is not necessarily balanced by good performance against other criteria (Figueira et al., 2016b). This non-compensatory behaviour means attributes can retain a baseline level which cannot be exchanged for improvement on another attribute. We can use this behaviour for environmental or cultural elements in our study to ensure a level of inherent value which cannot be lost. ELECTRE III can combine qualitative and quantitative attributes in the same study, allowing inclusion of impacts from gas hydrate development which cannot be quantified (Kangas et al., 2001). The ability to use many different scales in one study allows us to create the broadest and most complete protocol of gas hydrate development possible.

ELECTRE compares two actions and classifies the preference between the pair into one of three relationships (Figueira et al., 2016b). If the two actions are comparatively equivalent, then a state of indifference between the actions exists. If one action is judged as wholly superior to another, then a strong preference exists in favour of the superior action. If two actions are not equivalent, but there is insufficient information to adjudge one as wholly superior, then a weak preference exists for the superior action. ELECTRE III measures the presence of these relationships using a pair of indices, concordance and discordance, that are established through three thresholds, preference, indifference and veto (Figueira et al., 2016b). The indifference threshold defines the greatest separation that can exist between two actions that remain functionally equivalent. The preference threshold is the minimum difference between two actions for which a state of strong preference in favour of one action exists. The veto threshold is the maximum separation between two actions that still allows an overall strong preference in favour of the action judged inferior by the veto threshold in this evaluation. In essence, one action cannot be strongly preferred to another if, for any evaluation of the two actions, the action to be preferred is judged inferior by more than the veto threshold. The concordance and discordance indices quantify the preference relationships existing between two actions, a_1 and a_2. a_1 outranks a_2 if a_1 is always considered "at least as good as" a_2. The concordance index sums information that supports the evaluation of one action, a_1, as "at least as good as" the action it is compared to, a_2. This occurs where a_1 is preferred (strongly or weakly) to a_2, there is indifference between a_1 and a_2 or there is a weak preference in favour of a_2 over a_1. In the case of a weak preference in favour of a_2, this is insufficient to conclusively prove a_2 as superior, and as such, a_1 may be "at least as good as" a_2 once all information has been collated. The discordance index quantifies information opposing a_1 as "at least as good as" a_2, where there exists a strong preference for a_2 over a_1. The concordance and discordance indices are then used to calculate a credibility index, quantifying the overall credibility of a_1 as "at least as good as" a_2. When comparing many actions $a_1,a_2,\ldots a_n$, a superiority ratio for each action is calculated (Rao, 2013). The superiority ratio is the ratio of the sum of all credibilities of the action as outranking other actions to the sum of all credibilities of other actions outranking the action under consideration. Actions are then ranked in order of superiority ratio. Details of the mathematical formulation of ELECTRE III are given in Section 2.3.

4.3 Protocol Components

We have developed a multi-stage MCDA protocol for evaluating gas hydrate projects using ELECTRE III. This protocol is designed to be conducted by a facilitator on behalf of a decision maker, who has the final say on whether any program goes forward. The facilitator is presented with the general problem under consideration, and then collects and organises information to aid the decision maker. The MCDA process in this protocol can be summarised into eight distinct components (based on the approach of the Department for Communities and Local Government, 2009), which are also illustrated in Figure 4.1:

1. Identify and define the problem and the main goals and objectives.
2. Propose roughly defined alternatives to structure the problem.
3. With external input, constrain specific alternatives which meet this problem.
4. Identify and define criteria which evaluate how well the proposed alternatives succeed against the defined goals.
5. Appraise all alternatives against the evaluation criteria in an impact matrix.
6. Determine the stakeholder groups involved with the problem.
7. Use stakeholder input to derive importance weighting for the criteria used.

8. Combine criteria weights with the defined alternatives using ELECTRE III to establish a ranking order of suitability.

Each of these components is explained in the subsequent sections. There is some flexibility in the order in which these components can be completed. The final evaluation will be composed from combining the alternatives, criteria and weighting.

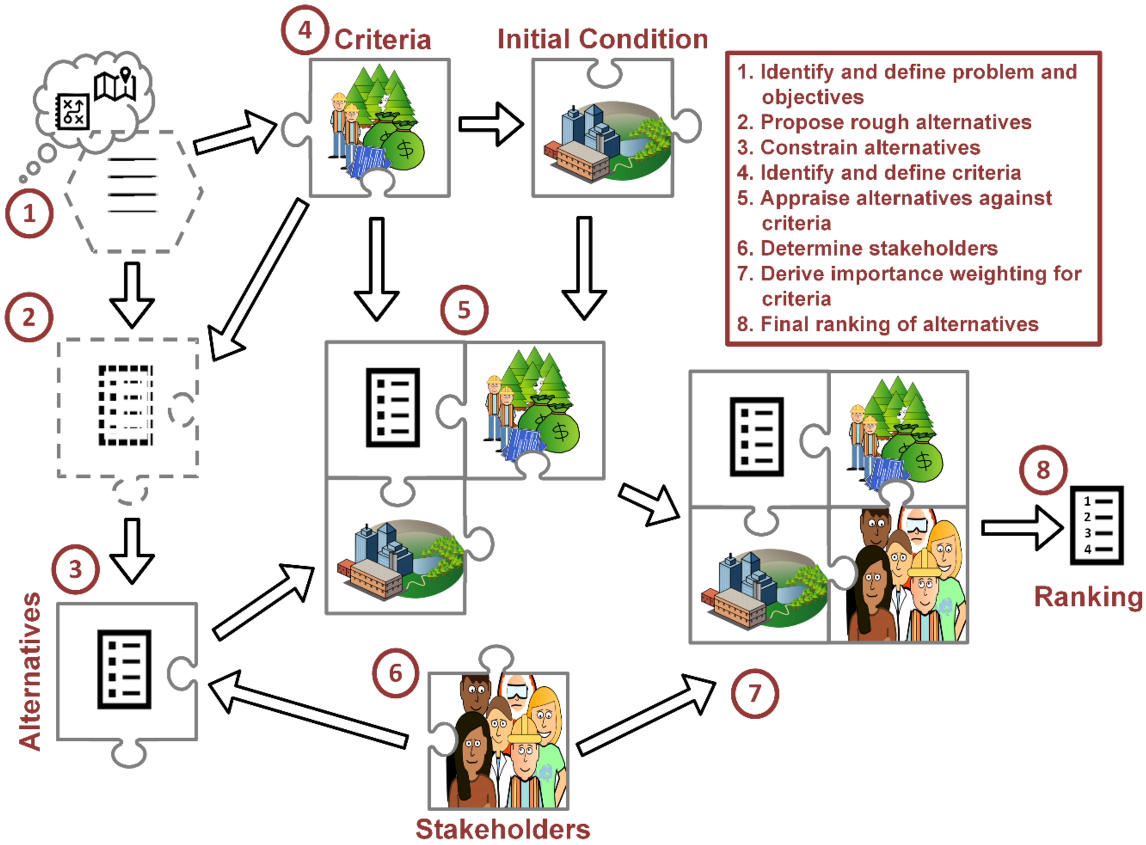


Figure 4.1 *Schematic of protocol steps, links between protocol steps and how each protocol component combines into the final product. Protocol steps are also iterative, and do not have to be followed in the sequence given here, until step 6. Dashed lines for step 1 illustrate the high malleability of the alternatives before determining criteria and receiving stakeholder input. Initial condition of site before proposed development occurs needs to be considered since any proposal will be an alteration to existing conditions.*

4.3.1 Identify and Define the Problem, Goals and Scope

The problem and overall goals of any potential solution must be defined first before moving forward with the protocol. The problem definition describes the situation where gas hydrate development is being considered to meet a commercial or social need. Stating the goals ensures that everyone involved with the study has the same expectations for the study outcomes. For example, if gas hydrate development is being considered in a region, the goal could be to determine if development is viable, or what form of development is most generally accepted. The study scope should be clearly determined at this stage by considering the resources available to conduct the protocol, as this information provides practical limits on the level of possible detail in the study.

4.3.2 Propose Rough Alternatives

Alternatives are different potential solutions to the problem in question. This phase should involve full exploration of the problem, first considering all possible courses of action and then selecting the alternatives that are appropriate to the location and resources available. Alternatives are compared by their impacts, establishing the future outcomes of pursuing given courses of action (Alcamo, 2009). The alternative of not taking any action should also be considered alongside development alternatives. Not taking action is a worthwhile alternative in our application: hydrate development may not be appropriate at all at a given location, or it may be appropriate, but not under present conditions.

At this stage alternatives are defined by the facilitator. These alternatives are deliberately kept loose in definition and will only be tightly constrained after external input at the next stage. Alternatives should be defined with enough variation that they differentiate within the process. Flexibility in the type of target problem allows this protocol to be used for many different comparisons in gas hydrate research. Different production styles which may be developed, including depressurisation, thermal stimulation and CO_2 exchange (Li et al., 2016), could be compared. Commercial considerations, such as different scales of development or different end markets can be used to derive alternatives, which allows the comparison of gas hydrate development alone or as an accessory to development of other resources that are generally located in the same regions as commercial gas hydrate prospects. Gas hydrate-specific legislation does not presently exist (Jackson, 2014), and different legislative scenarios could be explored to generate alternatives. Different alternatives could also be derived from the areas where large uncertainties remain in gas hydrate development, such as social and environmental risk.

4.3.3 Constrain Alternatives

Revisions to alternatives can be suggested by the decision maker, the facilitator after receiving more information, or the stakeholders, and alternatives may be further refined as the evaluation develops. This external validation is an early check within the process that proposed alternatives are appropriate and comprehensive.

This protocol uses an alternative-driven approach, rather than allowing the alternatives to take shape as a result of the study. The alternatives structure the rest of the analysis, which means that they must be defined before the analysis begins. However, one significant advantage of the ELECTRE III methodology is that, although fundamental changes to alternatives that change the problem under investigation require restarting the analysis, minor adjustments to alternatives can be made during protocol application without a complete restart. As gas hydrate commercialisation remains under development, many details of each alternative will be regularly changing, and this change may occur on shorter timescales than the duration of the assessment. Using our protocol, adjustments to alternatives can be made until the protocol is almost completed.

4.3.4 Identify and Define Criteria

Criteria assess the performance of each alternative under evaluation in meeting the goals of the problem. Criteria can measure alternative performance qualitatively or quantitatively as this protocol allows both types of criteria assessment to be used within the same study. Because this approach allows data to be brought together from different fields whatever the scale originally used for measurement, the protocol is inclusive of as much information as possible and can make best use of the limited information available on gas hydrate exploitation.

Since the impacts of gas hydrate commercial development are uncertain before it occurs, we must use experience of other similar commercial development to define our criteria. We analysed 104 papers that use MCDA approaches to energy and infrastructure development decisions to establish appropriate criteria that see common use in similar problems. Many of the works analysed were found through other literature reviews (Huang et al., 2011; Kiker et al., 2009; Mardani et al., 2017; Wang et al., 2009), and other works were found by keyword searching of citation indices. We considered potential impacts originating from both the direct gas hydrate exploitation and any distribution network necessary. When considering impacts, it is important to understand whether the area has experienced industrial development before, because such development changes how the area will respond in the event of gas hydrate development.

We have established five broad criteria classes which can be used to evaluate any potential gas hydrate exploitation project, shown in the hierarchy in Figure 4.2: Resource information, Economic factors, Social factors, Environmental factors and Infrastructure factors (Afgan et al., 2007; Wang et al., 2009). These criteria can be measured via a series of sub-criteria (Zangeneh et al., 2009). Including sub-criteria from each of these five criteria ensures the most comprehensive assessment of any project, especially in complex energy systems (Afgan et al., 2007). For a balanced assessment, similar numbers of sub-criteria from each main criterion should be used, but in some cases not all sub-criteria are applicable. Also, it may be difficult to find enough reliable data to evaluate all sub-criteria while gas hydrate development is still an emerging technology. Some sub-criteria can be measured in varying ways by focusing on different aspects. One such example is cost, which can be evaluated as a whole, but can also be evaluated using aspects such as initial cost, operational cost or profitability (Wang et al., 2009). When using aspects of sub-criteria, it is best to avoid using multiple aspects of one sub-criterion alongside overarching sub-criteria, as using multiple aspects can introduce double counting, where the same impact is evaluated multiple times under different guises (Department for Communities and Local Government, 2009).

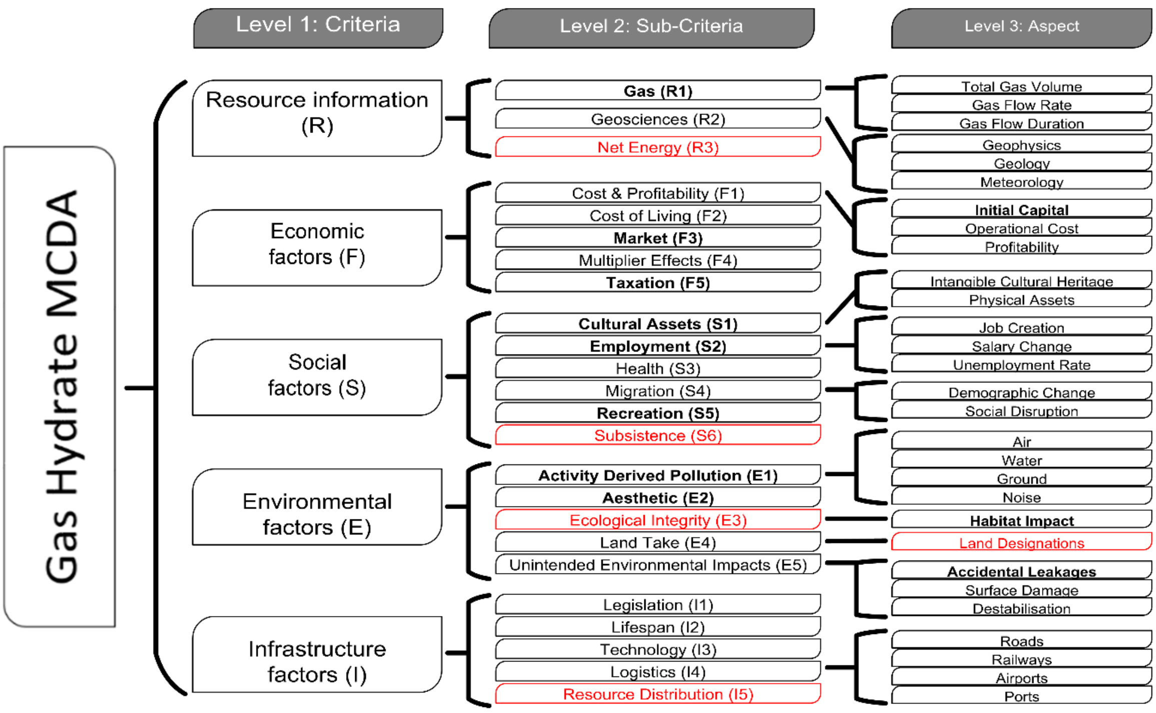


Figure 4.2 *Hierarchy of criteria and sub-criteria, with some potential aspects shown for certain sub-criteria. Criteria and sub-criteria highlighted in black were the full range from which criteria used in Alaska were selected, while red criteria and sub-criteria were suggested during protocol testing in Alaska. Habitat impact originally occupied the position of ecological integrity.*

The first set of criteria, resource information, evaluate aspects of gas production (R1) and other relevant geoscientific information (R2). R1 allows integration of factors such as resource size and rate and duration of gas production that may be estimated from quantitative models. R2 evaluates other information which may be relevant for drilling the resource, but does not affect gas production directly, such as local meteorology, which influences how much of the year drilling can occur (Soltanmohammadi et al., 2009).

Economic criteria evaluate financial and market elements including: measures of initial cost, operational costs and profitability (F1); changes to cost of living in the region due to changes in the local population or the products and services available (F2); quantifications of the gas demand and trade to different markets (F3); financial multiplier effects felt in related industries linked to gas hydrate development (F4); and tax revenue derived from production, distribution or sale of gas (F5) (Sólnes, 2003; Wang et al., 2009).

Social criteria evaluate impacts from gas hydrate development on the human sphere. These impacts include: impacts on resources which have specific cultural significance, for example to indigenous communities in the area (S1); changes in the number of positions or types of employment available (S2); impacts on physical or emotional health and wellbeing of those living or working in the area (S3); geographic redistribution of individuals resulting from changes in the natural or human environment (S4); and impacts on assets currently used for recreation and leisure (S5) (Soltanmohammadi et al., 2009; Tavana et al., 2013).

Environmental criteria evaluate impacts from gas hydrate development on the natural sphere. These impacts include: production of harmful pollutants which adversely alter the quality of any component of the natural environment (E1); visual damage from the proposed project footprint (E2); damage to animal habitats, especially those of endangered species or areas with an essential use in the life cycle of an organism, such as breeding grounds (E3); area of land which has its function changed from its current condition (E4); and unexpected failures in the system with potentially catastrophic effects, such as leakages, subsidence or thawing (E5) (Sólnes, 2003; Wang et al., 2009).

Infrastructure criteria evaluate impacts on existing infrastructure systems, including: regulation which can promote or hinder gas hydrate development (I1); the total duration for which operations will be active (I2); the technology and techniques available in the region to enable gas production (I3); and the network built to transport goods and personnel necessary in gas hydrate production (I4) (Tavana et al., 2013). Infrastructure criteria cover the presence or absence of physical assets that could develop the gas hydrate resource, as well as institutional infrastructure, none of which necessarily uses a market valuation. Cost to develop infrastructure would be evaluated separately using economic criteria.

Figure 4.2 shows all possible criteria that we believe may be considerations in gas hydrate development. Different criteria may dominate the decision making process in different settings. It is unlikely that all the criteria in Figure 4.2 would be used in a single evaluation, as our literature review found only 25% of studies used more than fifteen criteria. Our premise is that the optimum number of criteria for any study is the minimum number required to evaluate all aspects of a project (Bouyssou, 1990). Criteria can be omitted as redundant where all alternatives have the same or very similar performance, as such criteria would not aid discrimination between alternatives. In this case, a decision must be made about whether criteria with apparent limited impact on decision-making should be retained, in case they become discriminatory later if alternatives are adjusted. As commercial gas hydrate development evolves new criteria may emerge, so we would expect the hierarchy presented in Figure 4.2 to evolve over time. Criteria are used to refine the suggested alternatives (Figure 4.1) by focussing on what can be measured in each proposed alternative.

4.3.5 Create Impact Matrix

The impact matrix is a structured approach in which each alternative is evaluated by the criteria and sub-criteria included within the study. The impact matrix is an $N \times M$ organisational matrix, where N is the number of sub-criteria and M is the number of alternatives. Each element of the matrix gives the value for a specific alternative measured by a specific sub-criterion (Munda et al., 1994). Both qualitative and quantitative information can be displayed together within the same impact matrix. The assessment method must be the same for all alternatives on a single criterion to allow the values to be compared using the ELECTRE III methodology. Completing the impact matrix requires the facilitator to collect information from many different fields, which may have different assessment methods, different restrictions on information access or differences in information currency. Experts should be contacted from each field being evaluated to allow them to contribute specialist information, with multiple experts contacted to check the reliability of provided expert judgments. The facilitator then uses the impact matrix to collect expertise in a form which can be used by a decision maker who is not required to be an expert in all disciplines under evaluation. There are however many possible limitations on information availability. Criteria may have to be removed if well-constrained values cannot be calculated for a criterion against all alternatives using data from reliable sources. As commercial gas hydrate research is in its infancy, much of the technical information relating to production will have limited release, as entities protect their interests. In many environments where gas hydrate is found, research is challenging due to low location accessibility, resulting in large differences in the age of relevant information. With little research providing constrained social valuations, especially for use in a gas hydrate context, criteria which can be used in gas hydrate assessment are further limited.

4.3.6 Determine Stakeholders

Stakeholders are persons or entities with a vested interest in the outcome of the decision-making process (Schmeer, 1999). Stakeholders’ contributions ensure that different perspectives on a project are included in its final design, and ensure that the benefit and cost distribution is generally acceptable to most stakeholders. Buy-in from those involved will minimise potential future conflict and raise issues which can be resolved before these issues become hindrances to the project as a whole (Ansell and Gash, 2008). Including stakeholders in project assessment ensures that their interests are not misrepresented and helps shape development towards the most mutually beneficial form for all stakeholders (de Gooyert et al., 2017). Meaningful engagement with stakeholders allows participants to better understand the problem and decision making process, and ensures that each participant's views are taken into account (Marttunen et al., 2015). Stakeholders can get involved at many points in the process, allowing them to shape the alternatives or evaluation criteria used (Figure 4.1), or contribute insight later in the process through criteria weighting (Section 4.3.7). Rather than asking every single individual who may be affected by a project for their opinion, it is more feasible to group stakeholders with likely similar positions together and then attempt to involve at least one, but preferably multiple, representatives from each group (Palinkas et al., 2015). Failure to include certain stakeholder groups will likely bias the outcome of the process, so it is important that all positions are identified and represented to avoid an overly-homogenous network of stakeholders (Luyet et al., 2012). The process must be made transparent and accessible to allow all groups to contribute.

From reviewing stakeholders identified in related problems (Ord et al., 2007; Stein, 2013) we have defined six broad stakeholder groups:

1. Government (GOV)
2. Industry (IND)
3. Local Communities (LC)
4. Indigenous Communities (IC)
5. Environmental Organisations (ENV)
6. Scientific Community (SCI)

The government group includes the regulatory body that appraises gas hydrate development proposals, and is responsible for creating legislation and programs which can either encourage or restrict gas hydrate development. Government can have responsibility at local, regional, national or international levels, and different levels may have competing interests due to being accountable to different societal groups. In the case of gas hydrate, policy encouraging development may originate nationally, as with other unconventional resources (Wang and Krupnick, 2015). National government will also control most overseas trade dynamics and environmental regulation. More local government may use gas hydrate resources heavily in economic policy, and have variations in development regulation.

Industry stakeholders are representatives of organisations who would be involved with developing gas hydrate through the entire production and distribution chain, including organisations creating and operating associated infrastructure. Industry includes the workers involved with gas hydrate distribution, as well as the companies employing these workers.

The local community group represents those inhabiting the immediate area where gas hydrate is being developed, or inhabiting areas in the vicinity of infrastructure in the gas supply chain. Persons further afield may still influence or be affected by new gas hydrate development, such as through services funded by resource derived tax revenue. We limited the local community group to the zone surrounding gas hydrate infrastructure to introduce a reasonable constraint on the number of stakeholders who would have to be consulted to represent the local community group. In the case of offshore gas hydrate, local communities should be considered as the onshore area from where goods and services are supplied to offshore infrastructure.

The local community is distinct from the indigenous community, with the latter defined as having a long-standing historical tie to the region with their own distinct social, cultural or economic conditions (ILO, 2003), although the two communities may coexist spatially. Indigenous communities may have ownership or access rights to the land where development is planned and have the ability to greatly enhance or hinder development by exercising these legal rights (Dorobantu and Odziemkowska, 2017). Both the local and indigenous communities rely on the region, irrespective of any development, and will also experience the most direct impact from development of any group.

We define environmental organisations as non-governmental organisations (NGOs) focused on the environmental and social impacts of development over project economics, with a particular interest in promotion of sustainable development (Bendell, 2017). These organisations attempt to advocate for environmental issues, influence other bodies and sometimes directly act towards these goals. Environmental organisations can become involved in issues which are occurring distally, and often strongly oppose the development of non-renewable resources, such as gas hydrate, and also oppose heavy development in Arctic regions, where gas hydrate is often found (Busenberg, 2013).

For our purpose we define the scientific community as those involved in gas hydrate research directly, or involved in other research in a field included within the chosen evaluation criteria. These scientists would likely be involved in varying capacities should the resource be developed, including research and consultation.

It is likely that any person who may be affected by any given commercial gas hydrate development project can be classified into at least one of these groups. However, this categorisation should be interpreted flexibly to allow the participation of all relevant stakeholders. Individuals may be affiliated with multiple groups. All relevant stakeholder groups should be represented for a fair process, but in certain situations some of these defined groups may not be relevant if they have no connections to the affected area and would experience no direct or indirect impacts from any of the proposed development alternatives. Best attempts should be made by the facilitator to represent all stakeholder groups equally within the protocol and its final outcomes. The decision maker may choose to give different weight to the views of different stakeholder groups, but that should not be dictated by the protocol. The view within each of these groups towards any development is not necessarily unified, so it is important to gain the views of multiple representatives of each group to capture this variation. Gas hydrate development and its possible positive and negative consequences are not commonly understood beyond experts, so it is important the process informs and invites contribution from those who may be affected by a development they are currently unaware of.

4.3.7 Derive Criteria Weighting

Weighting is the technique used to mathematically represent the priorities of different stakeholders when they are considering the problem criteria, with more weight assigned to criteria that stakeholders find important, so these criteria have the greatest influence on the final result (Wang et al., 2009). By collecting weights from different stakeholders, the decision maker can assess which criteria are prioritised similarly by different groups, and where there are potential sources of conflict (Bryan et al., 2010). In ELECTRE, criteria weights and preference information are combined when calculating the concordance and discordance indices (Figueira et al., 2016b). The strength of preference in each criterion is derived by asking stakeholders to derive threshold values above which the difference between two alternatives is sufficient for the stakeholder to express a preference for one alternative over another (preference thresholds). The resulting strength of preference information for each criterion is multiplied by the weight of importance of that criterion, and the concordance and discordance indices are the sums of this weighted preference information. The strength of preference is shown mathematically in Section 2.3.

There are many different approaches suggested and used in MCDA for determining stakeholder weights. No specific weighting mechanism is defined for use with ELECTRE, so we have reviewed the methods used within the 104 papers we analysed to ascertain which is most suitable for our problem. Weighting methods encountered include direct allocation of weights, pairwise comparison of criteria (Saaty and Vargas, 2012), swing weighting (Lopes and Almeida, 2013) and the revised Simos procedure (Figueira and Roy, 2002). We chose to use the revised Simos procedure, in which criteria are presented to the stakeholder in the form of cards, which the stakeholder then orders by their importance (Figueira and Roy, 2002; Simos, 1990). Multiple criteria can be ranked as equally important, in which case each of the same rank criteria are given equal weight (Figueira and Roy, 2002). We have chosen this weighting procedure due to its accessibility to many different stakeholders, because it provides weighting based upon the intrinsic qualities of the criteria, not just the present situation, and because this approach does not introduce trade-offs, as this compensatory behaviour is not universally agreed as acceptable. We also use a weighting method without trade-offs to ensure consistency with the restrictions on trade-offs in the ELECTRE method.

4.3.8 Combination using ELECTRE III and Final Outputs

The impact matrix is weighted with input from stakeholders and then processed following the ELECTRE III methodology. The final results from the protocol includes complete criteria weights for all stakeholders and a ranking of alternatives. From these outputs the decision maker can understand both how well the alternatives meet the problem, and how appropriate the alternatives are to those involved. The decision maker can then use this information set for ultimately deciding between alternatives. The process can be iterative, by using the protocol results to refine alternatives before implementation, or to suggest new alternatives which can then be evaluated by the protocol again.

4.4 Case Study – Alaska

In order to test the suitability of our devised protocol, we used our approach to evaluate hypothetical gas hydrate development proposals in Alaska.

4.4.1 Gas Hydrate in Alaska

Significant reserves of gas hydrate are known to exist at the North Slope of Alaska, in areas of continuous permafrost onshore and in areas up to 120 m of water depth offshore (Collett, 1993; Collett et al., 2011a). The area where gas hydrate is potentially stable encompasses most of the north coast of Alaska, including around half of the National Petroleum Reserve and the area where conventional operations are concentrated at Prudhoe Bay (Figure 4.3), containing in excess of 1 trillion cubic metres of gas (Collett et al., 2011a; Wilson et al., 2011). This resource has been delineated through a series of well logging operations and production tests at the Mt Elbert and

Ignik Sikumi sites, and it remains an area of ongoing research (Ajayi et al., 2018; Nandanwar et al., 2016; Yuan et al., 2018). The large resource volume and local expertise in oil and gas development present the foundation for a possible business case for gas hydrate commercialisation.

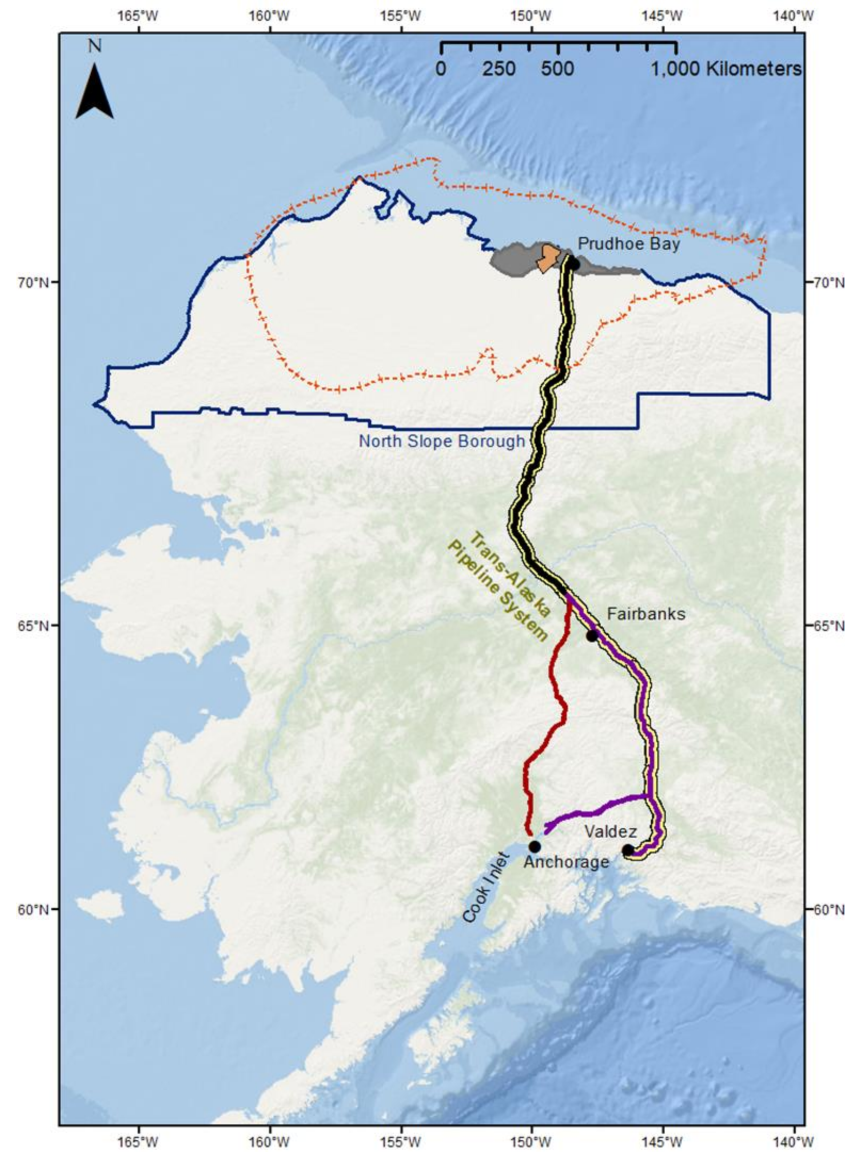


Figure 4.3 *Map of Alaska showing features relevant to our study. The orange region is the Eileen gas hydrate accumulation, which is the area we develop for gas hydrate. The solid grey region is the extent of the area that has currently been developed for conventional oil and gas and the dashed line shows the limit of the North Slope gas hydrate stability zone (Collett et al., 2011a). The Trans-Alaska Pipeline follows the yellow path. The black line is pipeline route common to alternative 2 & 3, once they diverge alternative 2 follows the red route and alternative 3 follows the purple route.*

Any gas exploitation at the North Slope is complicated by the large distance to the potential market, making distribution difficult. To solve this issue for conventional oil operations the Trans-Alaska Pipeline System (TAPS) was created. It has transported oil from the North Slope to the port of Valdez in the south of the state since 1977, but there is no equivalent infrastructure for gas transport. As it is not currently feasible to use large scale shipping to the North Slope, the most feasible transport method remains a gas pipeline to main population centres in the south of the state (Economides and Wood, 2009). The economy of Alaska is highly dependent on petroleum revenue, making future resource prices and production integral parts of Alaska's financial forecasting. Conventional production estimates are predicted to decline year-on-year, which will create a shortfall, which could be met by pursuing a greater breadth of resources including gas hydrate (Alaska Department of Revenue, 2018; Attanasi and Freeman, 2009). Therefore, Alaska has the potential to be one of the first onshore permafrost sites where gas hydrate is commercially exploited.

4.4.2 Alternatives for Pursuing Gas Hydrate in Alaska

We have devised four alternatives for potential gas hydrate exploitation in Alaska. The four alternatives are driven by different proposed end markets. These four alternatives are grounded as feasible projects, but they are not designed to match existing proposals closely, because this study was designed to test the protocol, rather than to gauge public opinion towards a specific proposed project. Also, during the initial alternative constraint, we experienced that a separation from real-world proposals made industrial and government stakeholders more comfortable in providing input. A succinct description of the alternatives is presented below, and more detail on these alternatives can be found in Appendix B.

- *A) Use in the immediate oilfield area*

In this alternative, gas hydrate development is small in scale and the gas generated is only used at the North Slope in oilfield operations. There is no development beyond the footprint of existing Prudhoe Bay operations. The gas from gas hydrate development would be used in the niche which is currently occupied by conventional gas.

- *B) Domestic use in-state*

In this alternative, gas hydrate development is expanded to meet the demands of the State of Alaska. Gas is used within the oilfield and also transported to the commercial and residential markets further south in the state. This transportation uses a pipeline running south from the oilfield to the Cook Inlet via Fairbanks, with offlets to allow gas to be distributed throughout the state.

- *C) Transport and export*

In this alternative, gas is exported to overseas markets, in addition to the gas used within the state and oilfield as described in the previous two alternatives. Gas is transported through a pipeline following a route close to the TAPS, to the port of Valdez in the south of the state and exported, primarily for use in the East Asian market.

- *D) Not exploiting gas hydrate*

In this alternative gas hydrate is not exploited, meaning it has no influence on operations at the existing oilfield, which will continue while there is economically recoverable conventional resource in demand.

4.4.3 Alternative Validation and Refinement

One industry, one scientific and one government stakeholder appraised the proposed alternatives to check their viability and that the theorised impacts were plausible, these stakeholders were not formally interviewed again. They declined to provide stakeholder weights later in the process, primarily due to contractual limitations on contributing opinions to published material. External participation was limited at this stage in our application of the protocol, so few stakeholders had the opportunity to shape alternatives or evaluation criteria. For future protocol applications, we recommend the process is more participatory and iterative, as shown in Figure 4.1.

4.4.4 Case Study Criteria

From those described in Section 4.3.4, the criteria chosen for this study were: volume of gas produced (R1), costs & profitability (F1), market (F3), taxation (F5), cultural assets (S1), employment (S2), recreation (S5), activity derived pollution (E1), aesthetic impact (E2), habitat impact (E3), and unintended environmental impacts (E5).

Geoscientific information (R2) was omitted as the wells would be drilled in the same location for all of our alternatives; R2 would have more discriminatory power if the protocol were used to evaluate between different possible gas hydrate deposits, where other drilling parameters such as depth to deposit or overburden material may also be relevant in decision making. Cost of living (F2) and multiplier effects (F4) were omitted because these are compound sub-criteria calculated from elements which are uncertain for this future projection, and as such we were unable to provide estimates of these impacts that were sufficiently accurate to allow stakeholders to make meaningful decisions between alternatives. Health (S3) was omitted because any gas hydrate specific human health impacts will only become apparent once gas hydrate exploitation commences, similar to the emergence of highly specific health concerns with the development of other unconventional gas resources (Sangaramoorthy et al., 2016). Migration (S4) was omitted because we chose to focus solely on employment and not consider the wider demographic and social changes that could be associated with gas hydrate development. Also, within Alaska there is a large community established in the area by previous resource exploitation, so migration is of less interest than in previously undeveloped regions. Land take (E4) was omitted as we focussed on land use changes which would impact habitats (E3), rather than the more general land use conversions measured by E4. Legislation (I1) was omitted because it has yet to be developed for gas hydrate production, and legislation changes significantly as administrations change, so it is impossible to predict at this stage. Lifespan (I2), technology (I3) and transport (I4) were not used for similar reasons, because gas hydrate production techniques are still being refined; these criteria can be included once relevant information becomes available. We also had to choose which criteria to prioritise with our limited resources, and these infrastructure impacts will be similar for the different alternatives within our case study. The lack of any infrastructure criteria reduces the completeness of this application of the protocol, but there was insufficient data available to create reliable estimates for any sub-criteria in this area.

The four alternatives for gas hydrate exploitation in Alaska were structured consistently using our chosen criteria to be readily comparable (Table 4.1). Both quantitative and qualitative criteria were used, depending upon which format was most appropriate for each criterion and what data was available. For criteria assessed quantitatively, we calculated impacts using available data in natural scales. The precise data and measurement method depended on the criterion. We utilised qualitative measurement for criteria where numerical data was not available, or where a single numeric value was insufficient to fully represent the impact. For example, the qualitative values we report for S1 combine impacts on registered cultural assets, size of affected caribou herds and size of local indigenous population centres, which would be difficult to summarise with a single quantitative value, but all of these measurements are intrinsically linked, and using multiple criteria would double count negative or positive performance from alternatives on the indigenous community. Criteria that were assessed qualitatively used a categorical scale with eight possible values for impact. These values are: none, very low, low, rather low, moderate, rather high, high, very high (Trochim et al., 2016). Due to our use of ELECTRE III, we are able to retain quantitative and qualitative criteria within the same study, as impact for each criterion is measured separately, and stakeholders provided thresholds to criteria individually.

The data sources and methods used to derive the estimates in Table 4.1 are given in Appendix B. The error margins on these estimates are used as the indifference thresholds in the evaluation, because two alternatives which differ by less than their respective error margin may be identical in reality.

Table 4.1 *Alaska case study impact matrix giving values for the four development alternatives against all criteria.*

		Alternative 1	*Alternative 2*	*Alternative 3*	*Alternative 4*
Resource	*Gas (thousand cubic metres/year)*	95	1425	3037	0
Economic	*Total Cost ($ billion)*	3.3	10.2	29.3	0
	Market ($/MMBTU)	9.3	10.9	16.4	15.0
	Tax ($ million)	70	200	600	0
Social	*Employment*	170	735	1710	0
	Recreation	None	Rather High	High	None
	Cultural Assets	Rather Low	High	High	None
Environmental	*Pollution (thousand tons CO_2)*	535	1000	1460	0
	Accidents (% gas fugitive release)	0.7	2.5	5.0	0
	Habitat Impact	Low	Moderate	Rather High	None
	Aesthetic	None	Rather High	Rather Low	None

4.4.5 Stakeholders Approached

Stakeholders were identified by contacting individuals from public records and media coverage of previous industry and scientific gas hydrate projects in Alaska, or by contacting individuals who had expressed an opinion on the future viability of gas development in Alaska before. Individuals who had shown an opinion on conventional gas development were found in records of public consultations on the development of in-state gas pipelines, or from relevant online or print media. Stakeholders were approached from our six groups (government, GOV; industry, IND; local community, LC; indigenous community, IC; environmental NGOs, ENV; and scientific community, SCI) to provide input on our potential gas hydrate development alternatives. Multiple stakeholders were contacted from each group to ensure a range of views. Contact information for stakeholders was found online, or through snowballing from existing contacts. Initial approaches were made by email or telephone to 156 people representing 90 different organisations. Overall, 87 people replied, eventually leading to 40 face-to-face or Skype meetings, including 16 stakeholders who agreed to formally participate in semi-structured interviews (Appendix C). The primary reasons for participants being unwilling to participate were a lack of perceived benefit to doing so and contractual obligations to not provide an opinion on record to external scientific studies. Interviews were conducted by the first author in English and lasted around an hour in duration. All stakeholders were provided with information on the topics to be covered and how their responses would be used prior to interview, to enable them to provide informed consent. When working with indigenous community representatives guidelines were followed for providing Free Prior and Informed consent (FPIC), to ensure stakeholders were informed of the study prior to participation and were free to participate or meet under conditions they found acceptable (Buxton and Wilson, 2013). The interviews were divided into three sections. In the first section, stakeholders were asked generally about their familiarity with natural gas development and gas hydrate specifically, how they viewed their position within the state and their views on future industrial development in the Alaskan Arctic. These questions established the stakeholder group represented by the individual and checked their knowledge was sufficient for them to provide usable responses. Stakeholders were then asked questions (Appendix C) to establish their criteria weights using the revised Simos' procedure. Stakeholders were finally asked ELECTRE specific questions (Appendix C), to establish preference thresholds on these criteria, with the ultimate aim of ranking the four project alternatives for each respondent. Collected stakeholder responses were anonymised and only attributed to their stakeholder group (IND, GOV, IC, LC, ENV, SCI). Stakeholders are referred to individually by a number within these groups (e.g. IND1, IND2, etc.).

4.5 Results

4.5.1 Criteria

We calculated the average weight of the four primary criteria (resource, economic, social, environmental) to compare the relative importance of these four areas (Figure 4.4a). Averages were used to remove weighting differences resulting from different numbers of sub-criteria.

The social criterion is valued lowest compared to the other three, with a mean weight of 15.3%, while the resource, economic and environmental criteria have mean weights of 29.9%, 28.7% and 26.0% respectively (Figure 4.4a). The social criterion is the only one of the four not prioritised as most important by any stakeholder. Weight given to the remaining three criteria ranges between 10% to 50% of total decision weight. For both resource and economic criteria there is much less consistency in weighting by those who weighted these criteria below average.

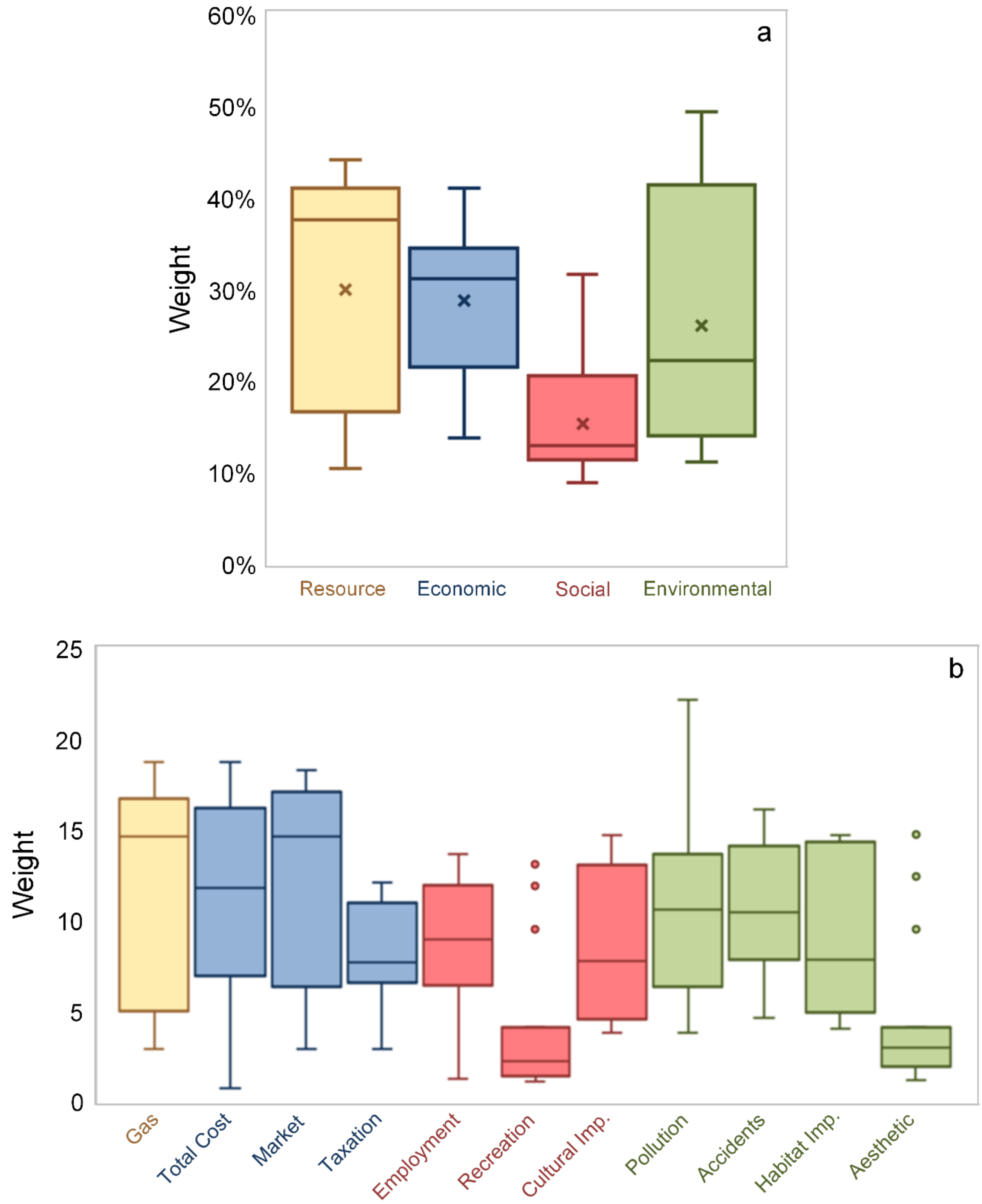


Figure 4.4 *a) Boxplots showing spread of average weight given to the four main criteria across all stakeholders, normalised as a percentage of total weight. Crosses show mean weights for each criterion. b) Boxplot showing range of weights given to each of the 11 criteria by all stakeholders. Circles show outliers. (a, b) Horizontal lines inside the boxes show median weights and the whiskers show values within 1.5 times the inter-quartile range of the upper of lower quartile.*

Recreation and aesthetic impact are given lower average weight than all other sub-criteria (Figure 4.4b). The justification for giving aesthetic impact a low weight was almost identical across all stakeholders, namely there would be little aesthetic impact with gas hydrate operations near existing infrastructure. For recreation, many stakeholders could not identify recreation assets likely to be adversely impacted, and in some cases new infrastructure was seen as beneficial for recreation by providing access to new areas. Gas volume and market show higher average weight than the remaining criteria, suggesting these criteria are most commonly given high importance in this decision context. Otherwise the median weights for the remaining seven sub-criteria are very similar (Figure 4.4b), suggesting a common level of importance for these economic, social and environmental factors. Excluding the two sub-criteria viewed as universally low importance, taxation shows the lowest spread in weighting. Taxation is a financial consideration for those developing the resource and will be dictated by governance, but will also provide revenue for services used by the remaining stakeholders, which may explain why it is weighted consistently. The remaining criteria show spreads in weighting from below 5% to over 15% of weighting (Figure 4.4b), suggesting that, despite similar median weights for each criterion, there is lower consistency in how individual stakeholders view these criteria.

When comparing individual stakeholders, the priorities of Alaskan society towards the development alternatives can be split into two rough groups (Figure 4.5). The first group is primarily concerned with the resource and economic criteria, and allocates over 60% of total decision weight to these areas. Members of this group are ENV1, IC1, GOV1-3, IND2-3 and SCI1-2. This group is primarily focussed on project return on investment; if a project is theoretically profitable social and environmental impacts will be made to fit within regulations, but these impacts will not determine whether a project is pursued. This group is directly opposed by those who allocate over 60% of their total decision weight to the environmental and social criteria. Members of this group are ENV2-4, LC1 and LC3. In this position, profitability is much less significant than the possible ecological impacts, and for certain individuals no development project may ever be seen as acceptable. Two stakeholders, LC2 and IND1, lie between these two opposite positions. Within each group stakeholders' weights differed for the criteria they did not prioritise, showing all stakeholders have some understanding and interest in both sides of the problem.

Amongst the four environmental stakeholders there is broad consistency in weighting for ENV2-4 (Figure 4.5), although ENV4 shows higher social weighting than other stakeholders. ENV1 is situated in the opposite position to the remaining environmental stakeholders, largely as a result of very low social weighting (8.8%). Of all the stakeholder groups, the local community representatives show the least consistency, as would be expected from such a diverse group. LC3 shows the most extreme environmental weighting (49.3%) of any stakeholder surveyed, perhaps representative of their interests. The remaining stakeholders from government, industry, the indigenous community and the scientific community all show consistent weighting, with only

IND1 as an outlier, who gives lower average weight to resource criteria and higher average weight to environmental criteria than other industry stakeholders (Figure 4.5).

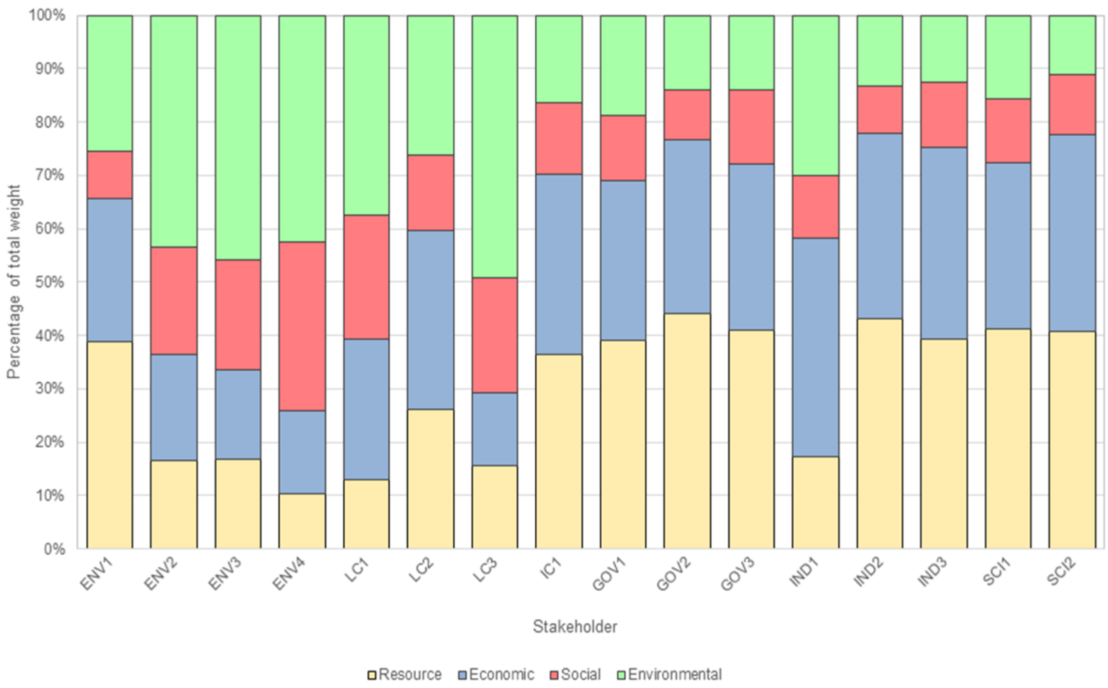


Figure 4.5 *Comparative breakdown of weight given to four main criteria areas by all stakeholders. Results presented as a proportion of total weight normalised to remove effects of different numbers of sub-criteria within each criterion. Stakeholder classification: industry, IND; government, GOV; indigenous community, IC; local community, LC; environmental, ENV; and scientific community, SCI.*

From the weights for individual sub-criteria, the two groups (group 1, over 60% of total weight to resource and economic criteria; group 2, over 60% of total weight to environmental and social criteria) are again clearly observed by the two red high-weight regions in Figure 4.6. For the first group most weight is concentrated in gas volume, total cost and market. Taxation is given less weight than other economic sub-criteria by this group. Employment and accidents are given noticeably higher weight than other environmental and social sub-criteria by members of this group. Interestingly, employment and accidents are measured quantitatively and the four qualitative criteria are universally given low weight by this group (Figure 4.6). Therefore, the low weighting of these four criteria may simply reflect their priorities, but it may also express an aversion from using qualitative information, which is seen as insufficiently objective (Spash and Vatn, 2006). Upon viewing all sub-criteria, ENV1 shows two main differences to other stakeholders of group 1, as ENV1 allocates significantly less weight to market and more weight to environmental sub-criteria. The position of stakeholders LC2 and IND1 between the two groups is shown by them allocating significant weight to sub-criteria from all four criteria (gas volume, total cost, market, employment, pollution and accidents).

	ENV1	ENV2	ENV3	ENV4	LC1	LC2	LC3	IC1	GOV1	GOV2	GOV3	IND1	IND2	IND3	SCI1	SCI2
Gas	15.1	5.0	5.0	2.9	3.9	9.1	4.6	14.2	15.4	18.8	16.7	5.6	18.3	15.9	16.8	17.0
Total cost	16.4	5.0	5.0	0.7	9.2	10.6	6.2	14.2	13.1	18.8	10.6	15.5	18.3	13.9	9.1	17.0
Market	9.6	5.0	5.0	5.8	7.9	16.7	2.9	14.2	14.2	15.1	15.2	17.2	18.3	17.9	18.3	17.0
Tax	5.5	8.1	5.0	6.6	6.5	7.6	2.9	11.1	8.3	7.8	12.1	7.3	7.4	12.0	10.6	12.0
Employment	4.1	9.7	8.9	8.8	2.5	12.1	1.3	11.1	11.9	7.8	13.6	8.9	7.4	6.0	12.2	12.0
Recreation	**1.4**	**1.8**	**1.1**	**13.1**	**11.9**	**3.0**	**9.5**	**1.8**	**1.3**	**4.1**	**1.5**	**2.3**	**3.8**	**4.1**	**1.4**	**2.1**
Cultural Imp.	**8.2**	**12.8**	**14.7**	**13.9**	**13.2**	**4.5**	**14.5**	**8.0**	**6.0**	**4.1**	**7.6**	**4.0**	**3.8**	**10.0**	**6.0**	**4.6**
Pollution	13.7	22.2	12.8	10.9	14.5	13.6	17.8	8.0	9.5	4.1	6.1	10.6	3.8	4.1	10.6	7.1
Accidents	11.0	15.9	12.8	10.2	14.5	15.2	16.2	8.0	10.7	7.8	9.1	12.2	7.4	8.0	7.6	4.6
Habitat Imp.	**12.3**	**12.8**	**14.7**	**14.6**	**14.5**	**6.1**	**14.5**	**8.0**	**6.0**	**7.8**	**4.5**	**13.9**	**7.4**	**4.1**	**4.5**	**4.6**
Aesthetic	**2.7**	**1.8**	**14.7**	**12.4**	**1.2**	**1.5**	**9.5**	**1.8**	**3.6**	**4.1**	**3.0**	**2.3**	**3.8**	**4.1**	**2.9**	**2.1**

Figure 4.6 *Heat-map showing weight given to each criterion by each stakeholder, with red indicating more weight and blue less. Each column is coloured individually from its maximum to minimum value. Bold rows indicate criteria that were measured qualitatively. Stakeholder classification: industry, IND; government, GOV; indigenous community, IC; local community, LC; environmental, ENV; and scientific community, SCI.*

From these results it is possible to suggest which impact areas should be prioritised when designing any future commercial gas hydrate proposal in Alaska. Recreation and aesthetic factors have less importance than other impacts to all stakeholders, but it is important to highlight that weight is context dependent. This result does not indicate that these impacts would be irrelevant in any proposal. Certain criteria, such as employment or accidents, were near universally seen as important, so achieving a positive, or at least very low negative, impact in these areas may be priorities when designing future gas hydrate development proposals.

4.5.2 Thresholds and Project Ranking

Of the 16 stakeholders interviewed, six gave full sets of preference (minimum difference between two alternatives for one to be strongly preferred to the other) and veto (maximum difference between two alternatives on one criterion while still allowing an overall preference for the alternative evaluated as inferior by this criterion) thresholds. Of all the sub-criteria included, market had the least discriminatory power, as a sufficiently low preference threshold to impact the decision was only chosen by one stakeholder. Habitat impact and cultural impact were the only sub-criteria given sufficiently low preference thresholds by all stakeholders to be discriminatory. Veto thresholds were only sufficiently low to influence the decision problem on some social and environmental sub-criteria, with economic vetoes provided less often and at values beyond the range of all alternatives here. Some stakeholders provided veto thresholds at values identical to or only very slightly above preference thresholds to represent a position where any negative impact would be sufficient to make development unacceptable. These low vetoes were used for cultural and habitat impact by stakeholders opposed to further development in the region. Although seen as the least important sub-criteria, recreation and aesthetic were commonly given low preference or veto thresholds, suggesting some inconsistencies between the two independent protocol sections (assigning weights and defining thresholds). In our problem context, recreation and aesthetic were given low weight as stakeholders did not anticipate significant impact from our alternatives on these assets, but stakeholders desired low impact in these areas generally, and as such allocated low thresholds when considering an impact occurring, meaning recreation and aesthetic cannot be assumed as universally unimportant beyond our problem context.

Project rankings were calculated for all stakeholders who provided thresholds. These calculated rankings shared two features. Firstly, alternative 4, the no development alternative, was always ranked as most preferred. Secondly, alternative 2, the pipeline for use in state only, was always ranked as the least preferred of the four alternatives, although sometimes as an equal to another development alternative. This result indicates that gas hydrate commercialisation is unlikely to be supported without a significant change in the general situation. However, alternative development proposals not considered here may be devised that improve the outlook for such commercialisation.

Two main calculated preference rankings exist (Figure 4.7). The first ranking was calculated for three stakeholders and corresponds to seeking the least development, with alternative 1 preferred next after alternative 4, then indifference between alternatives 2 and 3. This ranking arises from strict preference thresholds on environmental criteria, where little to no variation is allowed between alternatives before preference, and in some cases a veto, is expressed, with more relaxed thresholds for social and economic criteria. The inferior environmental performance of alternative 3 compared to alternative 2 is offset by its greater social benefits of increased employment and tax revenue. The other primary ranking, calculated for two stakeholders (Figure 4.7b), has alternative 3 next after alternative 4, with indifference between alternatives 1 and 2. In this ranking alternative 3 is calculated as the preferred form of development due to low preference thresholds on tax revenue and employment being sufficient to counter the higher environmental impact of alternative 3 compared to other development alternatives.

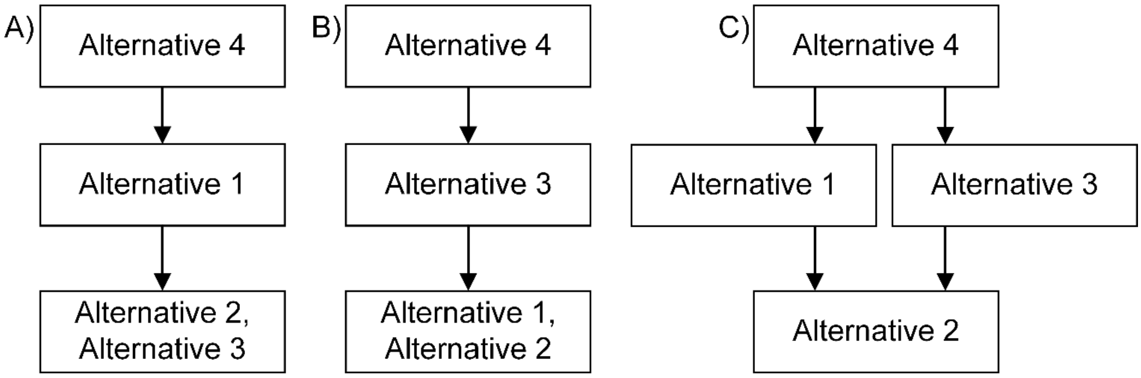


Figure 4.7 *Range of possible rankings of proposed alternatives calculated using ELECTRE III for Alaska stakeholders, with arrows indicating direction of outranking. c) The two unconnected alternatives are calculated as incomparable.*

For one stakeholder, both alternatives 1 & 3 had features making them simultaneously highly desirable and highly undesirable, which resulted in incomparability between these two alternatives for this stakeholder (Figure 4.7c, Deparis et al., 2012). Specifically, alternative 1 causes little environmental damage but also provides low tax revenue and employment, while alternative 3 provides much greater tax and employment, but at the expense of higher ecological impact. It is important to note that this situation only arises because alternative 4 outranks the remaining alternatives so strongly, and because of very low veto thresholds which are equal to indifference thresholds provided by this stakeholder. This result suggests that some stakeholders may be impossible to satisfy with any proposal, but greater exploration of these stakeholders' priorities is required.

4.6 Discussion

4.6.1 Ranking Validation

Project alternatives were discussed with stakeholders to establish which alternatives they found most viable and which they found most desirable, although the two answers often significantly overlapped. We used this information to validate the project rankings calculated from our protocol. Alternative 2 was rejected by stakeholders as highly unlikely to occur and largely undesirable as in-state demand was not seen as sufficient to justify or fund a project of this size. Alternative 1 was also often dismissed, as participants argued there is a surplus of conventional gas at the North Slope already. However, this alternative was considered plausible for conventional oil developments lacking a local gas supply, although participants thought that there are few locations where gas hydrate is found but conventional gas is unavailable. Alternative 3 was viewed as the most likely development option, although gas hydrate development would occur alongside conventional gas development to meet contracted demand. Alternative 4, the no development alternative, was preferred by many stakeholders, but for two distinct reasons. Alternative 4 was preferred by stakeholders who did not wish to see any further industrial development in the Alaskan Arctic or increased use of non-renewable resources, and also by stakeholders who would support gas hydrate development but not in the immediate future. Reasons for not supporting gas hydrate development at present include: unproven economic production, lack of any distribution mechanism to get gas to market, and oversupply of conventional natural gas in the same region. Overall, this evidence strongly aligns with the protocol results which had alternative 4 preferred and alternative 2 universally outranked. The main difference in alternative rankings between the direct interview information and protocol results is that some stakeholders expressed support for development (alternative 1 or 3), but the protocol always calculates no development (alternative 4) as the preferred alternative. In reality, stakeholders supporting development require an economically viable project, so the protocol results highlight that projected gas production from gas hydrate alone is insufficient to justify infrastructure development costs needed to supply this gas to any market, and the local oilfield market, where development costs are low as the infrastructure exists, is already oversupplied with gas, resulting in a lack of demand. Despite the good match between our protocol results and the interview results, we recommend that validation questions are included in future protocol applications to check that results calculated from expressed preferences match with stakeholders' intuitive responses.

4.6.2 Alternative Validation

During interviews, another alternative that we had not considered was repeatedly suggested as a potential future for gas hydrate development. Rather than developing a large-scale commercial project, gas hydrate could be used as a fuel source in isolated communities, requiring only small-scale development to meet demand. High fuel costs in these remote areas significantly raises living costs, and high polluting solutions such as oil and wood are currently used for fuel (Hossain et al., 2016). For communities lacking conventional gas, gas hydrate could provide a cheaper and cleaner fuel source. Indeed, gas hydrate sourced gas is potentially recharging the producing conventional gas field used by Utqiagvik, allowing longer production and a higher recovery rate than initially projected (Walsh et al., 2008). Although this alternative would require very high per capita investment, the North Slope Borough government has historically invested large sums received from taxing oil development into infrastructure for small, isolated communities (Tysiachniouk and Petrov, 2018). Even if the development is not profitable, it may be encouraged to improve energy security in remote communities that are currently using unreliable energy supply methods, such as fuel supplies by aircraft that are affected by weather (Hossain et al., 2016). As this alternative was repeatedly suggested by stakeholders from different backgrounds, in future protocol applications a more iterative participatory process, as shown in Figure 4.1, will allow the completeness of the alternative set to be checked.

4.6.3 Additional Criteria

During interviews, stakeholders were asked if the criteria used were sufficient to capture all their priorities. We compared any suggestions to the full list of criteria available, and as a result there are a small number of additional criteria we suggest as possibilities for future assessments (Figure 4.2).

Under the resource information criterion, net energy (R3) could be added. This sub-criterion evaluates the difference in energy received by the consumer and energy expended in transferring the resource to the consumer (Murphy and Hall, 2010). Net energy was put forward primarily due to the large distance that gas in Alaska needs to travel from production to market, but would be equally valid in any other setting where the location of production and market differ, which is common in resource exploitation (Ermida, 2014).

Under the social criterion, subsistence (S6), could be added. This sub-criterion evaluates the impact on the people, natural environment and species necessary to sustain subsistence (Loring and Gerlach, 2009), and as such is different from the evaluation of discrete locations suggested by cultural assets (S1). In Alaska there is a large indigenous population who wholly or partially rely on subsistence activities for their livelihoods, and other potential Arctic gas hydrate fields also have nearby indigenous populations (Fauchald et al., 2017).

Under the environmental criterion, habitat impact (E3) could be replaced as a sub-criterion by ecological integrity, with habitat impact becoming one aspect of ecological integrity. Ecological integrity more broadly evaluates the ability of a natural system to remain functionally close to a natural habitat by continuing to support diverse organisms and withstand external perturbations over an extended period (Parrish et al., 2003). Ecological integrity was suggested by stakeholders who felt the habitat impact sub-criterion was not comprehensive enough, as we defined habitat impact through spatial overlap of infrastructure with species' ranges, and using this broader measure should allay these concerns. Habitat impact would be used when the primary concern is the area used by one, or a group of, species. The aspect of land designations could be added to land take (E4). While land take considers the area of land whose function is changed, land designations focuses on lands which are classified for a specific use such as national parks, national monuments or wilderness areas (Jenkins et al., 2015). Indigenous lands are evaluated as cultural assets under the social criterion. Alaska has many areas with a designation that imposes controls on development such as national parks or wildlife refuges, and environmentally protected areas are a common influence on development locations worldwide (Prato and Fagre, 2005).

Under the infrastructure criterion, resource distribution (I5) could be added. This sub-criterion evaluates how the produced gas would be distributed to possible end users, especially whether communities near to gas transport infrastructure would be able to receive a gas supply, even if they are not the target market. This criteria is added in response to a concern raised during some interviews in Alaska over whether large, export-scale development would include sufficient provision for gas use in-state, particularly in small, low population communities along the pipeline route. This criteria would be measured by a qualitative statement of resource accessibility to the communities considered.

4.6.4 Limitations of the Case Study Example

4.6.4.1 Sampling

In future applications the process may be improved by involving stakeholders earlier, so that they can shape the alternatives and discuss which evaluation criteria are relevant (see Sections 4.6.2 and 4.6.3). Greater participation could improve stakeholder understanding of the process, which allows stakeholders to reach more informed judgement over a longer period of time than was possible in our study (Saarikoski et al., 2016). Increased participation also increases transparency, which may increase stakeholder buy-in, reduce suspicion of researchers' motives, and allow all groups involved to shape the process so that they will receive commensurate benefit from their participation (Munda, 2004). For participating, stakeholders should be able to expect at least feedback of the protocol results and conclusions, and also have the opportunity to build long-standing, mutually beneficial relationships.

4.6.4.2 Under-Representation of Indigenous Groups

Although identified as an important stakeholder in Alaskan development, the views of indigenous peoples are not reported equally to other stakeholders in the results section. Indigenous organisations were contacted during the research process, and in some cases agreed to meet and discuss the issue, but did not always provide their views in the same format as other stakeholders. As a result, there is only one indigenous stakeholder in Figure 4.5, although there were two further meetings and a number of email discussions on how appropriate our method was for Alaska Native stakeholders. Global attitude changes towards a more participatory research paradigm have made indigenous communities more selective in the researchers they engage with, as indigenous stakeholders seek to regain power in how research is conducted and how results are published (Koster et al., 2012). Therefore, indigenous stakeholders should be engaged earlier in the process in future, under conditions they define.

For sections of the indigenous community, the value structure imposed in this style of assessment is overly limiting, and cannot accurately represent their position (U.S. EPA, 2006). For stakeholders wishing to explain the emotional basis for their views, the Western weighting system used here lacks fundamental context; it is separated from the environment it is studying (Mazzocchi, 2006). Incorporating emotive aspects alongside other facets of resource evaluation is a long standing problem. The complex deep spiritual connection between people and land, and the narratives used to invoke this connection (Tuck et al., 2014), are beyond the capabilities of the protocol presented here and are possibly too profound for any such scheme. In order to incorporate this important dimension, sense of place could also be evaluated as a social construct (Brown, 2004). However, for some Alaskan Natives the economic returns cause development to be seen as worthwhile.

In a very simplified view of Alaska Native society, there appear to be two positions generated by an externally imposed organisational structure. The 1971 Alaska Native Claims Settlement Act (ANCSA) created 13 regional corporations and over 200 village corporations (Anders and Anders, 1986). As with any corporation, these organisations have a fundamental aim to maintain economic profitability which benefits their Alaska Native stakeholders. Simultaneously, there are Tribal governments which typically place higher importance on environmental issues and the maintenance of a subsistence lifestyle. This division is strengthened because tribal entities typically hold the surface rights to Native lands, while corporations hold the subsurface rights.

What both parties of Alaska Native society share is a desire for self-determination. Indigenous communities believe that, as the custodians of the natural resources in question, they should be given the same rights as any other community in determining how best to use these resources. As such, the community believes that the land should not be developed if those living there do not receive commensurate benefit from the development, but also development which would provide an agreed benefit should not be blocked by external actors who state they are acting in the interests of the community, to force the community to fulfil a role imposed upon them by those outside the indigenous community. The right of indigenous peoples to self-determination worldwide has been adopted by the United Nations (UNDRIP), which strengthens the position of indigenous groups in dictating how their land is used (Gilbert, 2016). The level of self-determination given to indigenous communities differs between countries, meaning the relationship between this stakeholder group and others present will vary significantly between global sites where gas hydrate may be developed.

This group remains a very important stakeholder both in Alaska and in other potential gas hydrate development areas such as the Canadian and Russian Arctic (Anderson et al., 2006; Degteva and Nellemann, 2013) and greater endeavours should be made to accommodate their needs in future appraisal. Part of the problem with our study specifically is that it involved a single research visit conducted on a hypothetical problem, with limited guarantee of a beneficial future outcome for participating. As such our research design unintentionally strayed troublingly close to a colonial style of research which is being eradicated from use in this environment (Tuck et al., 2014). As the first author who conducted the research was only fluent in English, there was no opportunity for stakeholders fluent primarily in Inupiaq to contribute, limiting input. To avoid under-representing this stakeholder group in the future, the process should be more participatory, allowing more co-production of knowledge (Armitage et al., 2011). Additionally, traditional knowledge should definitely be incorporated where appropriate, and especially in the evaluation of cultural and subsistence impacts, which are best understood by those experiencing them (Barnhardt and Kawagley, 2005). Traditional knowledge should be incorporated according to existing guidelines, such as the Nagoya protocol and the Convention on Biological Diversity (Buck and Hamilton, 2011; Posey and Dutfield, 1996). Lifestyles at the North Slope were traditionally nomadic and so wide areas of the landscape have some traditional association, not just the communities in which Alaska Natives now reside. Boundaries of sites such as natural parks were not necessarily created using input from the indigenous community living there, and so using these designations to determine impact is inadequate for certain criteria. Instead, more credence should be given to the determination of those whose culture is being evaluated on whether or not resource development is appropriate.

It is important to note that discussion of the limited overall benefit to participation was not unique to Indigenous stakeholders, and this shortcoming was one of the main limitations on willingness of contacted stakeholders to meet or actively participate. If the protocol is being used to evaluate upcoming commercial proposals, it is likely the audience would be more receptive, as their input may have more consequence to their lives.

4.6.4.3 Issues Raised with Defining Thresholds

While all participants completed the weighting section, only six participants provided preference and veto thresholds. The thresholds were supplied to stakeholders in the form of a slider which may have led to anchoring effects (Green et al., 1998) where the slider ranges were used for guidance on criteria thresholds. The precise value for any threshold was defined by positioning an indicator on the range slider, but some stakeholders used indicator position rather than the corresponding value (stakeholders positioning the indicator in the centre of the slider range if they had little prior knowledge, as the central value on the slider was assumed to be an “average” threshold value), suggesting the value stakeholders provide could be altered by changing the slider bounds. This behaviour could be utilised in future by carefully controlling slider value ranges to translate stakeholders’ qualitative inferences to quantitative information.

There were a number of reasons given by stakeholders for not providing preference thresholds. For some respondents there was an issue in data quality, as stakeholders felt their preference thresholds would be smaller than the data error margins. This issue should be alleviated as more reliable data are produced, which is likely as gas hydrate production becomes closer to a commercial reality and more resources are invested into determining the impacts associated with this production at any specific site. Other stakeholders self-identified a hypothetical bias (Murphy et al., 2005), and so felt it was impossible to accurately express their values. A number of stakeholders argued that the problem was inherently a trade-off and therefore no project would be preferred or excluded based upon its performance on a single criterion. The decision problem was often described as a trade-off by those heavily weighting economic criteria, suggesting a familiarity with compensatory economic methods such as cost-benefit analysis.

Stakeholders who provided thresholds were generally confident in doing so in their area of expertise, as well as in areas of little interest to them. In the latter case, stakeholders provided large thresholds or omitted thresholds entirely to ensure low weight criteria had little to no impact on the final decision. The primary area of concern was providing thresholds on criteria where stakeholders desired to provide a reasonable threshold, but lacked enough knowledge to quantify this value. The qualitative criteria proved easier to provide thresholds for, as a precise numeric value was not required. When interviews were conducted most, if not all, participants struggled to provide threshold values for at least some criteria. We suggest three possible approaches for defining thresholds in future applications to minimise this issue:

1) Increase decision support to avoid stakeholders having to provide precise quantitative values. Thresholds are defined either as a result of positioning of a slider with defined ranges, or repeatedly splitting the difference between proposed threshold values until the stakeholder is satisfied. This approach could be practical in future protocol applications with greater time and workforce, and where stakeholders are willing to make larger time commitments.

2) Use experts to provide threshold values. Stakeholders provide thresholds only on criteria where they are confident, and thresholds from all stakeholders are combined into a single

series for the decision problem. Each threshold can be provided by a single expert stakeholder or averaging the input of all confident stakeholders. Group deliberation could be used to provide thresholds if the experts were collected into one location. This approach has many practical similarities to the original protocol. Alternatively, if a range of thresholds are collected, the extremes can be explored to see how this range affects the final decision.

3) Make all thresholds the responsibility of the overall decision maker. A single set of preference and veto thresholds are used throughout, with stakeholders providing different weighting schemes only. This approach relies upon the decision maker being able to provide thresholds on all criteria and reduces stakeholder influence on the final decision. We do not recommend this approach as it does not fit with the generally participatory nature of the protocol. Individuals using the protocol may consider this approach as it requires the least external input, but wider stakeholder involvement should be sought whenever possible.

4.7 Conclusions

4.7.1 Alaska

The repeated ranking of no gas hydrate development at the Alaska North Slope as the preferred alternative is supported by the absence of current commercial development. For gas hydrate development to become viable, a change is needed in the market situation, as well as proof of the resource as technically and economically recoverable. As a large export development is the most viable commercial alternative, the fortunes of gas hydrate development are contingent on commercialisation of conventional gas in the region, which would develop the infrastructure needed to export gas hydrate-derived gas. Gas hydrate production may show most viability as a local source for isolated communities, especially where it improves energy security.

Our study identified two opposite positions in Alaska, where one group focussed on project economics and the other on the social and environmental consequences. The two positions are internally consistent in weighting and preference ranking, suggesting these views dominate the debate surrounding resource development, although there is evidence some Alaskan stakeholders consider both sides equally. Those looking to develop gas hydrate or similar resources should make greater effort to consider all criteria during design, rather than focussing only on project economics. Although compromise may be possible, the strict preference and veto thresholds expressed by some stakeholders illustrate that it may be impossible to satisfy all stakeholders simultaneously with any development. The Alaska Native community is under-represented in our work, and future appraisal should make greater efforts to adequately represent their views. Additionally, traditional knowledge should be incorporated into the protocol to more accurately measure impacts where appropriate.

Although some criteria are shown as of low importance to all stakeholders, this result does not mean these criteria should be excluded from future appraisal, as these criteria are only low priority in the decision context presented here, and so should be included in future appraisals with different contexts. There are many potential criteria that we have not included, including some suggested during the course of research, which may also be important considerations in future decision problems.

4.7.2 Protocol

This protocol is a major advancement as the first evaluation of the business case for gas hydrate development and the associated environmental and social impacts, creating a framework for any future evaluation to follow. Our protocol proved successful at translating stakeholder responses into consistent logical preference rankings. Weighting especially proved accessible to stakeholders from a wide range of backgrounds, improving the inclusivity of our method. Weighting successfully identified trends in preference across many stakeholders, highlighting the primary considerations in similar decision contexts. Preference thresholds were more complex and as such experienced a lower completion rate, but this can be remedied in future protocol applications, preferably by relying on sub-sets of stakeholders to provide thresholds, or increasing decision support.

Our protocol considers a range of market and non-market elements within a single evaluation framework. Many stakeholders gave weight to qualitative criteria measuring social and environmental impacts, which are beyond the scope of conventional approaches such as CBA. Additionally, the attitudes of some stakeholders in viewing certain assets as too valuable to compromise supports the non-compensatory behaviour of our protocol, as some impacts cannot be justified by financial remuneration.

Although successfully applied to Alaska the versatility of the protocol needs to be established by application to different gas hydrate developments worldwide. This protocol is equally applicable to other resource management and planning problems when attempting to simultaneously appraise economic, social and environmental impacts with a range of stakeholders, as long as care is taken to choose appropriate appraisal criteria.

Chapter 5 Further Protocol Applications

To be a widely applicable tool, any assessment protocol needs to be proven across the range of possible gas hydrate commercialisation sites. My protocol test in Alaska covers onshore development in an Arctic environment with a history of resource development, but little domestic gas production, so I consider broader applicability to geographically and socially distinct gas hydrate sites. To this end, I present hypothetical gas hydrate development projects of the style where this protocol may be used at the Mackenzie Delta, Canada, the Messoyakha field, central Russia, and the Nankai Trough, offshore Japan. At each location, I define synthetic gas hydrate commercialisation alternatives using secondary data and suggest means by which impacts could be assessed qualitatively and quantitatively in a future assessment, then I use scenario analysis with a range of preference and veto thresholds to rank these alternatives, providing example protocol results to discuss any limitations or caveats with the process. With the range of alternatives and criteria considered by these case studies, I am able to refine and finalise the protocol structure, correct operational discrepancies, and establish best practices for future applications.

5.1 Introduction

Gas hydrates are a global resource, but are found in two primary settings, offshore continental slopes, and onshore and offshore areas with large-scale permafrost (Ruppel and Kessler, 2017). Although their geological properties can be similar, these environments are far less homogeneous socially and environmentally. In Section 2.4 I defined five main criteria for evaluating potential gas hydrate developments (Resource Information, Economic, Social, Environmental and Infrastructure), all of which are impacted differently in different locations. Even where the development style is similar, the initial condition of the area will vary in many ways:

- The hydrate resource may be able to support intensive production for a long duration, or it may be much smaller in scale or more complex and costly to develop.
- Development may be intended for local use or export to distant markets.
- There may be large local population centres, or the region may be mostly uninhabited.
- Habitats and biomes will vary between geographic locations depending on the climate.
- The area may have a history of similar development resulting in significant infrastructure, or the region may be otherwise unindustrialised.

- Regional government may support or hinder commercial development through legislation.

As a result, any gas hydrate assessment protocol must be highly adaptable. I describe potential gas hydrate development in three settings with similar and contrasting features to the Alaska North Slope: the Mackenzie Delta, north-west Canada; the Messoyakha field, western Siberia; and the Nankai Trough, offshore Japan. These scenarios present a series of hypothetical problems where my protocol could have use for comparing alternative proposals in future.

For comparison, as described in Section 4.4, the Alaska North Slope has a large onshore resource in an area which has seen extensive oil and local gas development (Wilson et al., 2011), but lacks infrastructure to distribute produced gas to market (Economides and Wood, 2009). The natural environment is Arctic tundra, with a limited local human population composed mostly of indigenous peoples (Brinkman et al., 2014). The government has experience with similar pre-existing industry that will form the basis for technological and geographical restrictions on gas hydrate development (Collett et al., 2011a).

The Mackenzie Delta has many natural similarities to the Alaska North Slope, lying 500 km east of Prudhoe Bay, just across the Alaska-Canada border (Ashford et al., 2012a). Socially, both regions have a local indigenous population who rely on similar species for subsistence (Natcher, 2009). Unlike Alaska, the Mackenzie Delta has not been developed for natural resources, despite known conventional oil and gas resources, meaning the area is closer to its original natural state, but also does not have a steady stream of hydrocarbon revenue in the regional budget (Joint Review Panel for the Mackenzie Gas Project, 2009). Additionally, infrastructure and legislation for natural resource development are much less established in the Northwest Territories than in Alaska. Therefore Canada (Section 5.2) may consider gas hydrate development if the returns justify its impacts in a region relatively lacking in comparable development.

Conversely, the Messoyakha field (Section 5.3) lies in western Siberia, a region intensively developed for natural gas, so gas hydrate commercialisation here could readily be integrated into existing systems to distribute gas to market (SRI Earth and City, 2018). Climatically, the Messoyakha field is similar to both Alaska and Northern Canada, providing a similar habitat (Forbes et al., 2009), although this field is further onshore and different species are present, as the sites occupy different continental landmasses (IUCN, 2019). In keeping with other Arctic sites, there is a limited, predominantly indigenous, local population (Forbes et al., 2009). The government has heavily promoted resource exploitation, and it remains part of long-term regional strategy (Institute of Energy Strategy, 2010), so development here will face lower legislative opposition.

Finally I present the Nankai Trough (Section 5.4), which is distinct to all other locations, as it requires offshore gas hydrate development in a non-Arctic environment. As offshore continental shelves are a major environment where gas hydrate is found (Ruppel and Kessler, 2017), it is important to establish how the protocol can be applied to these sites. Although there is no population directly coincident with the development field, large cities along the Japanese coastline could provide the base for developing this resource, and the market for gas supply (Ishwaran et al., 2017). The offshore setting provides a different habitat to consider, and different environmental considerations, as gas hydrate is found here with a much thinner overburden than equivalent resources onshore (Fujii et al., 2015). The Japanese government has also invested heavily in gas hydrate technology while seeking a domestic natural gas source (Oyama and Masutani, 2017).

In the rest of this chapter, I introduce each location and describe any previous gas hydrate investigation in the region. For each site, I present representative commercial alternatives that I evaluate through criteria encompassing the most relevant impacts. I suggest how these impacts could be measured in each case, providing a range of qualitative and quantitative approaches with considerations for future applications. In lieu of field investigation, I use scenario analysis to create synthetic results and show the protocol suitability in each case, highlighting any issues and suggesting possible refinements.

5.2 Mackenzie Delta, Canada

The Mackenzie Delta lies at the extreme north of the Northwest Territories (Figure 5.1), a sparsely populated region of Canada with a predominantly tundra, forest and mountainous environment. The region has experienced a series of short-lived resource booms starting with gold in 1899, followed by oil in 1921 and then fur trade until the 1950s (Joint Review Panel for the Mackenzie Gas Project, 2009). The territory is now dependent on revenue from gold and diamond mining, with most mines in the east near the territorial capital, Yellowknife (Pearce et al., 2011). The Mackenzie Delta is estimated to have significant hydrocarbon reserves, which has attracted industry for pilot projects, but large-scale industrial development has not emerged, as it is remote from any major market, lying 180 km north of the nearest town, Inuvik (Ashford et al., 2012a) and 250 km east of the border with Alaska. As with development of the similarly isolated Alaskan oil reserves at Prudhoe Bay, there have been large pipelines proposed to transport oil or gas from the Mackenzie Delta to markets in southern Canada, beginning in 1973 (Gibson, 2011). This proposal pre-dated the Trans-Alaska Pipeline System, which was constructed between 1974-1977, and proposed to link the newly discovered Prudhoe Bay field in Alaska to the Mackenzie Delta, then transport gas from both fields to Alberta (White, 2012). This project was derailed when its social-environmental impact assessment recommended a ten year moratorium on pipeline development while land ownership issues were resolved with the indigenous peoples of the region (Berger, 1977). In Alaska, indigenous land ownership was resolved by the Alaska Native Claims Settlement Act in 1971, allowing TAPS construction (Busenberg, 2011). During this moratorium, other gas projects in Alberta reduced the target market for any Mackenzie project (Gibson, 2011). A new pipeline following the Mackenzie Valley was proposed again in 2000, but changes in market conditions while the impact assessment process was ongoing reduced government and industry support (Gibson, 2011), resulting in the project ultimately being scrapped in 2017 (Strong, 2017).

The presence of gas hydrate beneath the Mackenzie Delta has been known since the early 1970s when it was reported in commercial exploration wells (Bily and Dick, 1974). 263 wells have been drilled in the Mackenzie Delta coastline and offshore shallow continental shelf, identifying 2.7×10^{13} m^3 of conventional gas and between 2.4×10^{12} m^3 and 8.7×10^{13} m^3 of methane in gas hydrates (Majorowicz and Osadetz, 2001; Osadetz and Chen, 2010). The higher estimate for gas hydrate is less constrained as conventional gas is the primary commercial target, with gas hydrate at shallower depths than most exploration operations. Gas hydrate is found in ten layers at depths between 900 to 1100 m (Dallimore and Collett, 1998), with hydrate saturation ranging from 50%-90% (Kurihara et al., 2012). Gas hydrate stability is controlled by 600 m of overlying permafrost that creates suitable pressure/temperature conditions (Ashford et al., 2012b). The gas hydrate composition is 99.5% thermogenic methane, originating from the deeper conventional petroleum system (Dallimore and Collett, 1998). Scientific test wells have been drilled specifically for gas hydrate at the Mackenzie Delta Mallik site in 1998, 2002, 2007 and 2008 (Ashford et al., 2012a). Early well tests were conducted primarily to core and measure the hydrate in place, aiming to quantify the resource (Collett and Dallimore, 1998). The 2008 test monitored gas and water flow during six days of depressurisation-induced production (Ashford et al., 2012b). This test was conducted primarily to test logistics and well construction in an Arctic gas hydrate environment.

I have chosen the Mackenzie Delta as a case study for gas hydrate commercialisation as the site shares many environmental and cultural similarities with the Alaska North Slope, but has not seen the same intense industrial development. I present three potential development alternatives of Mackenzie Delta gas hydrate, covering the range of possible project scales. I compute the protocol with appropriate criteria evaluating economic, social and environmental impacts with hypothetical weighting schemes informed by my Alaska North Slope assessment (Section 4.4).

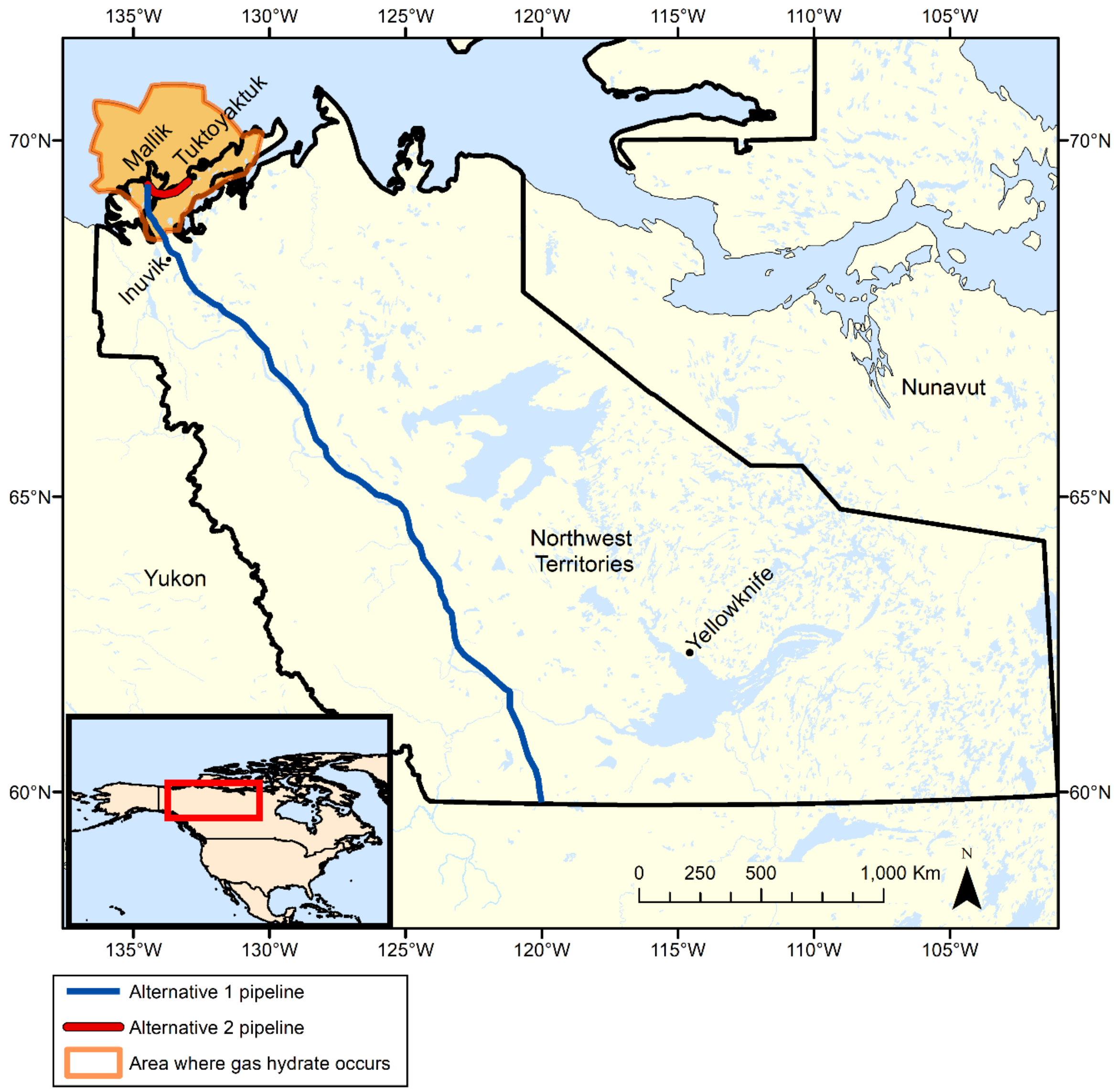


Figure 5.1 *Map of industrial development alternatives within the Northwest Territories (black outline). Bodies of water are shown in blue. Gas hydrate location is based on the area defined by Osadetz and Chen (2010). Location of the main map within North America is shown by the red line on the inset.*

5.2.1 Alternatives

I suggest three different scales of gas hydrate development for different end markets, based upon prior project proposals and local needs (Figure 5.1):

1) A gas-hydrate anchored version of the Mackenzie Valley pipeline project (Nuttall, 2008). A pipeline transporting gas through the Mackenzie Valley has been proposed multiple times, anchored by conventional gas fields. By contrast, my alternative uses a similar transport route, but has gas supplied instead by intensive development of the gas hydrate field. The suggested pipeline route follows the Mackenzie River to the border with

Alberta, where the gas can be connected to the existing Canadian national network. Additionally, this pipeline could supply gas to small, predominantly indigenous communities along the route, such as Inuvik, that currently have limited or unreliable energy supplies (Nuttall, 2008).

2) Use gas hydrate to supply gas to Tuktoyaktuk, replacing diesel fuel. As in most remote Canadian communities, Tuktoyaktuk relies on a diesel generator for electricity generation, and this solution is expensive to supply and run, with fuel flown or barged into the community (Basbous et al., 2015). Gas hydrate derived gas could be produced locally from a well at Mallik, providing a cheaper fuel source as it has lower transport costs. Using natural gas would also create fewer pollutant emissions than diesel, improving air quality and health in the village population (CBC News, 2011a).

3) No gas hydrate development. The Mackenzie Delta has significant undeveloped conventional hydrocarbon resources due to environmental concerns and large distances between the resource and markets. Canada began a five-year moratorium on drilling in Arctic waters in 2016 in response to fears about climate change, so resource development may be restricted in the region (Shapovalova and Stephen, 2019). Renewable energy sources such as wind power could also be used in remote communities for cheaper and cleaner reliable energy, especially if subsidised by the government (Basbous et al., 2015). Alberta and British Columbia both have large gas reserves that could be developed, which are closer to the population centres where the gas is needed (Stephenson et al., 2012). Accordingly, gas hydrate development at the Mackenzie Delta may not align with government policy or the strategic goals of the hydrocarbon industry.

5.2.2 Criteria

For assessment I use the following criteria: gas supply (R1); capital cost (F1); cost of living (F2); employment (S2); migration (S4); subsistence (S6); pollution (E1) and land take (E4). Criteria omitted due to a lack of information or being beyond the scope of this case study are: geosciences (R2), net energy (R3), market (F3), multiplier effects (F4), taxation (F5), cultural assets (S1), health (S3), recreation (S5), aesthetic impact (E2), ecological integrity (E3), unintended environmental impacts (E5), legislation (I1), lifespan (I2), technology (I3), logistics (I4) and resource distribution (I5).

Gas and capital cost measure the economic fundamentals of the project, as my experience in Alaska shows that projects are only considered if they are economically sound. I use cost of living as a criterion to quantify the reduction in energy costs if the produced gas replaces imported fuels. Employment and migration evaluate the positive and negative impacts of job creation in these alternatives. New job creation is often touted as one of the main benefits of any new industrial development, but the small regional population could experience social upheaval due to worker migration, so I include measures of both sides. The regional population is predominantly indigenous, and subsistence remains important to culture, livelihoods and wellbeing, so I evaluate how this industrial development may disrupt subsistence resources. Canada has strict environmental policies that have restricted regional industrialisation (Shapovalova and Stephen, 2019), so I assess the high water production caused by gas hydrate production, as pollutant control or treatment will likely be mandated in any development. Gas hydrate production produces very high levels of water compared to conventional gas production, producing freshwater that may mix with production fluids, which can be discharged into the freshwater river, or offshore. As the region is industrially undeveloped, I evaluate the land take of each alternative, considering land that may be lost, especially if it currently has environmental protection. Impacts for each alternative are summarised in the impact matrix (Table 5.1). In subsequent sections I provide further detail on the impact of each alternative as evaluated by each criterion, and the origins of the values in Table 5.1.

Table 5.1 *Impact matrix for the three proposed alternatives for Mackenzie Delta gas hydrate development.*

		Alt 1. Mackenzie Valley pipeline	Alt 2. Supply to Tuktoyaktuk	Alt 3. No hydrate development
Resource	Gas (m^3/day)	$1x10^7$	$1x10^5$	0
Economic	Cost ($CAN million)	10500	88	0
	Cost of living (reduction in electricity cost)	33%	33%	0
Social	Employment (persons)	550	15	0
	Migration (persons)	800	0	0
	Subsistence	High	Moderate	None
Environmental	Pollution (m^3/day)	16000	160	0
	Land Take (km^2)	5850	5	0

5.2.2.1 Gas

A commercial gas production rate from gas hydrate at the Mallik site is difficult to predict without a long-term production test, but short term production test results can be extrapolated to provide a rate estimate (Dallimore et al., 2012). In the 2008 depressurisation test, gas production ranged from 1000–4000 m^3/day, increasing over the duration of the test (Kurihara et al., 2012). Numerical modelling suggests the ultimate production rate could be $1x10^5$ m^3/day or higher, only limited by the ultimate quantity of resource (Uddin et al., 2012). Seismic imaging has established that the deeper gas hydrate zones extend hundreds of metres from the well locations, potentially supporting a large commercial operation (Dallimore et al., 2012).

For alternative 1, the Mackenzie Valley Pipeline was designed previously with a capacity of 3.3 million m^3/day (Joint Review Panel for the Mackenzie Gas Project, 2009). To supply this volume of gas purely from gas hydrate would require over 300 wells, which is unreasonable for the field area. Conventional gas fields were planned to provide two-thirds of pipeline capacity to encourage further resource development, so gas hydrate should not be anticipated to fill the entire pipeline capacity (Joint Review Panel for the Mackenzie Gas Project, 2009). Instead, pipeline infrastructure will encourage further hydrocarbon exploration of the region, making the Mackenzie Valley region a major gas supplier to Canada, so capacity must be retained for other development (Gibson, 2011). Therefore, I model gas hydrate providing the shortfall between conventional-sourced gas and the total pipeline capacity, requiring 100 wells across the gas hydrate field. In this case study I focus on gas hydrate development, and do not consider whether other resource development will proceed and use the pipeline. Additional pipeline usage provides additional need for a pipeline development, but would also cause social and environmental impact over a wider area, so could be the subject of future study.

Tuktoyaktuk is supplied by three diesel generators with a total capacity of 2.21 MW (Northwest Territories Power Corporation, 2014). The three gas generators in Inuvik have individual capacities between 2.1–2.8 MW (Northwest Territories Power Corporation, 2014), so one gas generator could meet the needs of Tuktoyaktuk. Total gas supply to the three generators in Inuvik was $5x10^4$ m^3/day, so estimated production rates suggest that a single gas hydrate well would be sufficient to supply a Tuktoyaktuk gas generator (National Energy Board, 2019).

5.2.2.2 Cost

For alternative 1, the field would be developed using a series of connected wells, with a central facility for processing gas, before transmitting the processed gas to demand centres by pipeline. I estimate well costs from the current cost of developing wells at the Alaska North Slope, as the environment is comparable and construction costs would likely be similar (Thomas et al., 2007). Additionally, to develop and operate the pipeline requires new road and airport infrastructure along the pipeline route. Road infrastructure is under construction along the length of the Mackenzie Valley, which would reduce pipeline development costs and allow equipment and personnel to be transported in from southern contractors (Department of Transportation, 2009; Government of the Northwest Territories, 2019). The primary target market for this alternative is the larger population centres or industrial hubs in Alberta and southern Canada, not necessarily local use. With the large scale pipeline development in alternative 1, the small population sizes of the villages in the Mackenzie Valley may be insufficient to justify a gas off-take, especially further from the pipeline route, as connection costs increase with increasing distance. Pipeline connections are more likely for Inuvik (population: 3536), Fort Good Hope (570), Norman Wells (818), Tulita (531), Wrigley (114), Fort Simpson (1296) and Jean Marie River (89), all of which lie directly on the pipeline route, while communities further afield such as Tuktoyaktuk (population 982, 85 km from the pipeline route) or Fort McPherson (population 684, 130 km from the pipeline route) would not be cost effective to supply with gas (Government of the Northwest Territories, 2018; National Energy Board, 2010). Connecting these seven valley communities would still cost over $100 million, and it is unclear whether this infrastructure would be funded by the pipeline operator or the territorial government, as the commercial returns would be low (National Energy Board, 2010). In these communities, converting power generation facilities from diesel to natural gas could cost up to $7.5 million per facility, and the average cost to retrofit each household would be $2300 (Canadian Gas Services International, 2012), at least part of which would have to be covered by the government to incentivise the fuel switch (Zellen, 2008). In total, project capital costs for pipeline, field and infrastructure development are $10500 million (Joint Review Panel for the Mackenzie Gas Project, 2009).

For alternative 2, I estimate capital costs based upon the conventional Ikhil gas field that supplied Inuvik, and existing valuations for connecting communities to the Mackenzie pipeline. I estimate $50 million for a single well development (CBC News, 2011b) and $30 million for 70 km of pipeline (Canadian Gas Services International, 2012) due to the difficult terrain, adverse weather conditions for construction, lack of related infrastructure and the environmental sensitivity of the region, necessitating stringent production controls. Tuktoyaktuk would also have to be converted from diesel fuel to natural gas, as for the local communities in alternative 1, resulting in total alternative 2 cost of $88 million.

5.2.2.3 Cost of Living

The Northwest Territories is cold and experiences long hours of darkness for much of the year, necessitating high energy use for heating and lighting (Government of the Northwest Territories, 2008). Remote communities are isolated from large energy grids, meaning each community must have its own electricity generation and back-up systems, resulting in no economies of scale that usually reduce the end user cost for energy (Government of the Northwest Territories, 2008).

Combined with high fuel costs, as fuel has to be flown or shipped into communities, energy contributes to living costs in the region being 50-60% above those in Canadian urban areas (Erber et al., 2010). The high cost of living is causing regional population decline, especially in small communities, as people are unable to support rising living costs on the limited wages available (Standing Senate Committee on Energy, the Environment and Natural Resources, 2014). A reliable gas supply would align gas prices in Northwest Territories with the rest of Canada, making living in the region cheaper and potentially reducing out migration (Dana et al., 2008).

In Inuvik, using locally produced natural gas instead of heating oil reduced annual heating costs by almost half (Government of the Northwest Territories, 2011a). While supplied by natural gas Inuvik also had the lowest electricity price of any Northwest Territory community (Northwest Territories Power Corporation, 2011). Switching to natural gas results in a 20% reduction in electricity cost, as the levelised cost of electrical energy (LCOE) for Inuvik from diesel generation is \$0.390/kWh, compared to a cost of \$0.305/kWh for natural gas (Pinard et al., 2015). When the Inuvik gas supply terminated abruptly due to well failures and overestimation of resource size, heating costs rose by 83% in a single year (CBC News, 2014). Most Northwest Territories' communities use diesel, which has an average electricity rate of \$0.68/kWh, although this is subsidised by the government to \$0.30/kWh to reduce living costs (Northwest Territories Power Corporation, 2019). Using gas instead would reduce government spending on subsidising energy, providing more revenue for other government services, or reduce the consumer electricity rate if the saving is passed on. This subsidy is a relatively new policy, consolidating over 200 rates that depended on location and energy usage (Forrest et al., 2009). Before subsidisation, two communities supplied by natural gas had average energy prices of \$0.35/kWh, while the average price in diesel supplied communities was \$0.96/kWh (Northwest Territories Power Corporation, 2002). Using historical and current pricing data for the territory, I estimate that switching from diesel to natural gas would reduce energy costs by approximately one third. This reduction in cost of living would be available to consumers supplied by natural gas in either alternative, although not all communities could be supplied with gas, even in alternative 1.

5.2.2.4 Employment

New employment opportunities are commonly cited as a major benefit of any new extractive industry development, and are used as a major incentive when seeking government support (Barth, 2013). As I focus on the long term impacts of the project, I only consider permanent employment created. There would be temporary employment along the length of the pipeline in alternative 1, potentially employing thousands of persons, but these positions would be seasonal and last for five years at most (Joint Review Panel for the Mackenzie Gas Project, 2009). Income spent in the local economy during this construction boom will not necessarily adjust the social situation permanently (James, 2016). For operational employment, I base my estimates on proposals for similar Mackenzie Valley pipelines or comparable field developments. I estimate production field employment using the values calculated for Alaska (Section 4.4), as the technology required is similar. I estimate 150 permanent positions to maintain and monitor the pipeline and facilities, mostly at the north end of the pipeline, but with others in communities through the valley (Joint Review Panel for the Mackenzie Gas Project, 2009). Large industrial projects in the Northwest Territories have target levels of indigenous employment, improving access to opportunities within this region and sustaining a mixed economy (Gibson and Klinck, 2005). Members of the local community may receive training opportunities as a result, providing potentially valuable skills, but these skills may not be transferable to any other work in the region, as there are unlikely to be multiple large pipeline developments in the near future. The local community is predominantly indigenous, but may be unable to access employment opportunities if the working schedule is not compatible with subsistence needs (Angell and Parkins, 2011), although many communities have established food sharing networks between hunters and other community members that would enable some to participate in a wage economy, while others continue in a subsistence economy (Collings, 2011).

In alternative 2, developing gas for Tuktoyaktuk creates few new permanent positions, as once developed the field could be monitored remotely (Kiggiak EBA Consulting, 2011). Workers with appropriate construction skills are present in the local area, as 70% of workers on the Inuvik to Tuktoyaktuk highway came from local communities, so even temporary positions may not change local employment (Bennett, 2018).

5.2.2.5 Migration

If employment opportunities are not filled by the local community, workers would migrate from outside the region, pursuing well paid gas development jobs. Migration is a societal concern in Canadian Arctic communities, as other resource development has been accompanied by issues including drug use, violent crime, prostitution and housing shortages (Young, 2016). Workers in the frontier oil and gas industry acknowledge a culture of frequent drug and alcohol use, as they receive a high income, have few diversions, and drugs are freely available despite being illegal (Goldenberg et al., 2010). Public opinion is such that local communities have expressed a desire that any temporary oil and gas workers be housed in enclosed camps, with no contact allowed between workers and local residents (Joint Review Panel for the Mackenzie Gas Project, 2009). Restrictions on alcohol vary across the Mackenzie Valley, including some areas where alcohol is prohibited, creating a black market for these goods (Davison et al., 2011). Increasing infrastructure connectivity could lead to smuggling into rural communities lacking services to handle the issues these substances create (Bennett, 2018).

Construction could provide up to 5000 temporary jobs per year, mostly filled by workers who fly in seasonally (Finnegan and Jacobs, 2015) but, as I only include permanent employment in my employment estimate (Table 5.1), I only consider corresponding permanent migration. Mackenzie Valley pipeline income and employment is estimated to motivate 400 workers to migrate to the area permanently (Joint Review Panel for the Mackenzie Gas Project, 2009). Although most migrants would be young, single males, another 400 family members may also migrate to the area (Joint Review Panel for the Mackenzie Gas Project, 2009). Many of these workers would settle in Inuvik as the closest major settlement to the field (Government of the Northwest Territories, 2018), and existing housing and services here are already insufficient (Young, 2016). While potentially less disruptive than those migrating in during construction, there would still be cultural and lifestyle differences between these new migrants and the indigenous population.

Alternative 2 is unlikely to cause migration, as few new positions are created, and sufficient skilled labour exists in the local community. Tuktoyaktuk has experienced a steady population decline since 1996 due to high living costs and a lack of career opportunities (Kiggiak EBA Consulting, 2011), so providing gas to the community may partially address these issues and slow this decline, with an overall result of no net migration (Bennett, 2018). Individuals migrating for employment are less likely to migrate to small indigenous communities, as these are more isolated, and do not have necessary services for the lifestyle these individuals seek (Joint Review Panel for the Mackenzie Gas Project, 2009).

5.2.2.6 Subsistence

Subsistence hunting has a long history throughout the Northwest Territories for survival and commercial trading, and continued subsistence hunting helps preserve indigenous cultural values (Natcher, 2009). Of the different indigenous communities inhabiting the region (Figure 5.2), 47% of Inuvialuit, and 29% of Dené (of which Tlicho, Deh Cho and Sahtu are major ethnographic groups) and Métis fish or hunt for subsistence, and these resources are traded throughout communities, so most indigenous peoples here utilise some subsistence resources (Government of the Northwest Territories, 2015). In Tuktoyaktuk, 50% of the community rely on subsistence as their primary food source, as other food sources have to be imported from communities further south, using channels that are easily disrupted (Andrachuk and Pearce, 2010). I explore the impact of each alternative on subsistence by establishing which species are significant, and exploring how each may be affected by resource development.

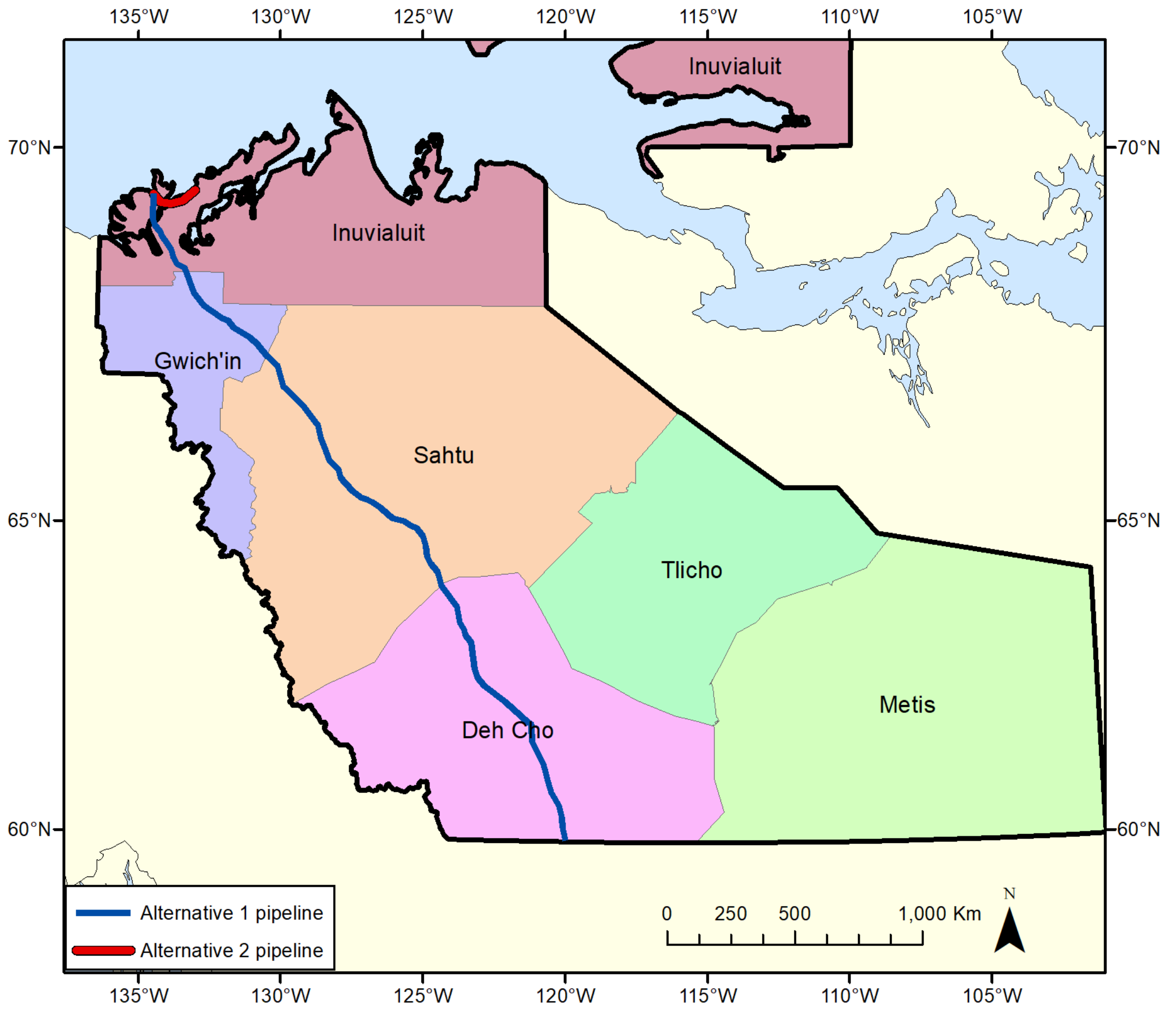


Figure 5.2 *Map of approximate ethnographic divisions within the Northwest Territories (black outline) (Parlee, 2012), overlain by alternative infrastructure routes.*

The Mackenzie Delta is the most ecologically diverse and productive region of the Canadian Arctic (Betts, 2005). Species used for subsistence vary, based on local availability and needs. For the Inuvialuit important species are caribou, beluga whales, whitefish (cisco, trout, inconnu, herring) and geese (Andrachuk and Pearce, 2010). Inland, the Gwich'in use moose, caribou, furbearers (beaver, marten, muskrats, hare), waterfowl and whitefish (Government of the Northwest Territories, 2011b) and further inland the Dené hunt moose, caribou, bear, furbearers (beaver, muskrats, marten, lynx, wolf, fox), birds, cod and burbot (Smith, 1986).

Two caribou herds are found in the area affected by both alternatives, between Mallik and Tuktoyaktuk, the Cape Bathurst herd (2000 animals) and the Bluenose-west herd (17500 animals) (Kiggiak EBA Consulting, 2011). The alternative 1 route also cuts through the calving area of the Porcupine caribou herd (Berger, 1977), in addition to the ranges of the Bluenose and Bathhurst caribou further south, and this pipeline and associated infrastructure could impede migration routes (Nicholson et al., 2016). Existing human development has already caused a 70% decline in regional caribou populations in the last two decades due to habitat loss in infrastructure construction (Parlee et al., 2018), and further development could enhance this decline. Large mammals (e.g. wolf, bear, lynx), found discontinuously throughout the delta are threatened by habitat loss, defensive shootings and sport hunting (Follmann and Hechtel, 1990). Increasing regional human population, and improving accessibility through new infrastructure, could increase human interactions with these species, providing a greater threat. Smaller furbearing mammals are similarly threatened by increased hunting and habitat loss, both of which are greater threats with increasing scales of industrialisation. Water fowl have limited viable habitat in the region, so the Mackenzie Delta is used as a breeding ground or stopover habitat for over 100 species of migratory bird (Betts, 2005), harvested for subsistence in both Alaska and Canada (Wolfe et al., 1990). As the delta coincides with the area where hydrate is modelled to be stable, field development would rapidly erode this niche habitat. The Mackenzie River contains over 60 fish species (Betts, 2005), including anadromous migratory species caught in communities along the Arctic coastlines of Canada and Alaska (Fechhelm et al., 2007). As the Mackenzie River is a spawning ground, damage to this area could decimate fish stocks (Howland et al., 2009). Spawning (and subsistence fishing) can occur hundreds of kilometres upstream, including in tributaries of the Mackenzie River, and alternative 1 follows the river valley, potentially impacting its full length (Dessau, 2012). Fish would be impacted by any change to water chemistry or temperature that may result from industrial run-off, and development could input sediment into the river that impedes the channel, which would restrict migration (Bodaly et al., 1989). The nearshore bay area between the field and Tuktoyaktuk is a calving area for marine mammals that is accessible by boat, and as such is used heavily by the local community (Waugh et al., 2018). Large marine mammals here could be impacted by habitat damage, especially loss of areas vital to their lifecycle, as well as direct mortalities from boat strikes.

Overall, the estimated impact on subsistence is higher for alternative 1 than alternative 2 as a greater range of species are impacted over a wider area. The pipeline route proposed follows the river channel due to terrain accessibility, but this area is also some of the highest quality habitat, and is most accessible for the local communities. As the delta provides temporary habitat for migratory species, subsistence communities will be impacted in other countries, not just the immediate area. Alternative 2 has a relatively high impact on subsistence for the scale of development, as the area affected is scarce habitat used by many species, and it is used during critical life phases, such as breeding. For my qualitative assessment of subsistence I combine the size of affected area, number of species affected and usage of these species into a single measure.

5.2.2.7 Pollution

In northern Canada surface water is often used residentially with minimal treatment, including for human consumption, so water quality standards for development projects are necessarily strict (Joint Review Panel for the Mackenzie Gas Project, 2009). Canada imposes project specific regulations on waste water discharge that consider environmental risk, available technology and project economics when defining limits (Lee and Neff, 2011). More broadly, the properties of the Arctic Ocean are heavily influenced by river water and nutrients, and this controls the life supported there (Emmerton et al., 2007). Gas hydrate wells produce water at over a hundred times the rate of conventional gas wells (Walsh et al., 2009), and introducing produced water from wells could change the delta and nearshore environment.

In the 2002 operational test at Mallik, drilling fluids were disposed via a sump, where shallow subsurface temperatures froze waste drilling fluids in place, before being covered (KAVIK-Stantec Inc, 2015). Permafrost degradation can compromise the integrity of drilling sumps (Thienpont et al., 2013) so this is not considered a viable long term solution, and in the 2007 and 2008 operations environmental concerns resulted in all waste material being transported off-site by truck (Ashford et al., 2012a). However, in a large commercial operation the number of trucks needed to match production would not be cost effective, and would overwhelm the limited road network available. Therefore, in a permanent commercial operation, most produced water would be processed and reinjected into the formation through dedicated wells (O'Rourke and Connolly, 2003). Unlike the fluids from conventional production, gas hydrate exploitation produces fresh water, but will gain low concentrations of impurities from production chemicals and formation dissolution. As such, the water could not be used directly, and would require treatment if any use was desirable.

In addition to planned water production, there is the possibility of accidental discharge, which was a noted issue in the 2007 and 2008 tests (Ashford et al., 2012b). Better procedures would reduce the number of fluid spills per well during a commercial operation, but the high volume of produced water and remoteness of the site would make fluid spills and clean-up a continuous production risk. With low pollutant concentrations, the produced water is unlikely to be directly toxic, but long term exposure of any species can decrease community health through a succession of gradual changes in species fitness (Lee and Neff, 2011). In the offshore hydrate zone, produced water may be discharged directly into the water column, introducing dissolved or particulate matter that can have a long term influence on the health of marine organisms (Camus et al., 2015). Mallik is a low-lying coastal site that can be inundated by storm surges, so there is potential for violent mixing between sea water and any fluids on site (KAVIK-Stantec Inc, 2015).

Onshore, the presence of near continuous permafrost will trap spilled water discharge in the shallow subsurface, affecting surface water but not deep aquifers. In the 2007 test an ice pad, a thick solid ice platform separating production from the tundra beneath, was used to reduce direct spills onto the permafrost (Ashford et al., 2012a), and this would likely be used in any commercial development.

A commercially producing well at Mallik is estimated to produce 160 m^3/day of water (Kurihara et al., 2012). I define the impact of each alternative through the total daily water production that has to be processed for the field, scaling this well production estimate for the number of proposed wells in each alternative.

5.2.2.8 Land Take

I evaluate land take by quantifying the total land area likely to require special development consideration, either because the land is owned by an indigenous group, or because the land has been identified as having environmental significance. Indigenous land ownership was a major obstacle for the first proposed Mackenzie Valley gas pipeline (Berger, 1977), and before any industrial development could proceed there would have to be agreements in place with all tribal governments involved. Environmentally, infrastructure development on Arctic land is often controversial, and where protection designations exist these are often used to formally oppose industrial development, such as the Arctic National Wildlife Refuge (ANWR) in Alaska (Kotchen and Burger, 2007).

The different indigenous groups (Tlicho, Deh Cho, Sahtu, Gwich'in, Inuvialuit) throughout the Northwest Territories (Figure 5.2) have negotiated separate land claims with the Canadian government, shown in Figure 5.3 (Langton, 2006). Some of these land claims have existed in their current state since the early 1990s, but future negotiations are always possible. Land claims are a mixture of surface and subsurface rights. Developing the pipeline route would require surface land use agreements with the Inuvialuit, Gwich'in, Sahtu and potentially the Deh Cho. Of the proposed 1300 km pipeline route for alternative 1, 52 km is through Inuvialuit land, 105 km through Gwich'in lands, 247 km through Sahtu lands and 272 km of the route over potential Deh Cho land. The Tlicho negotiated for surface and subsurface rights over a single broad region, with the ability to renegotiate if relevant laws change (Langton, 2006), but this region does not include any section of the pipeline route.

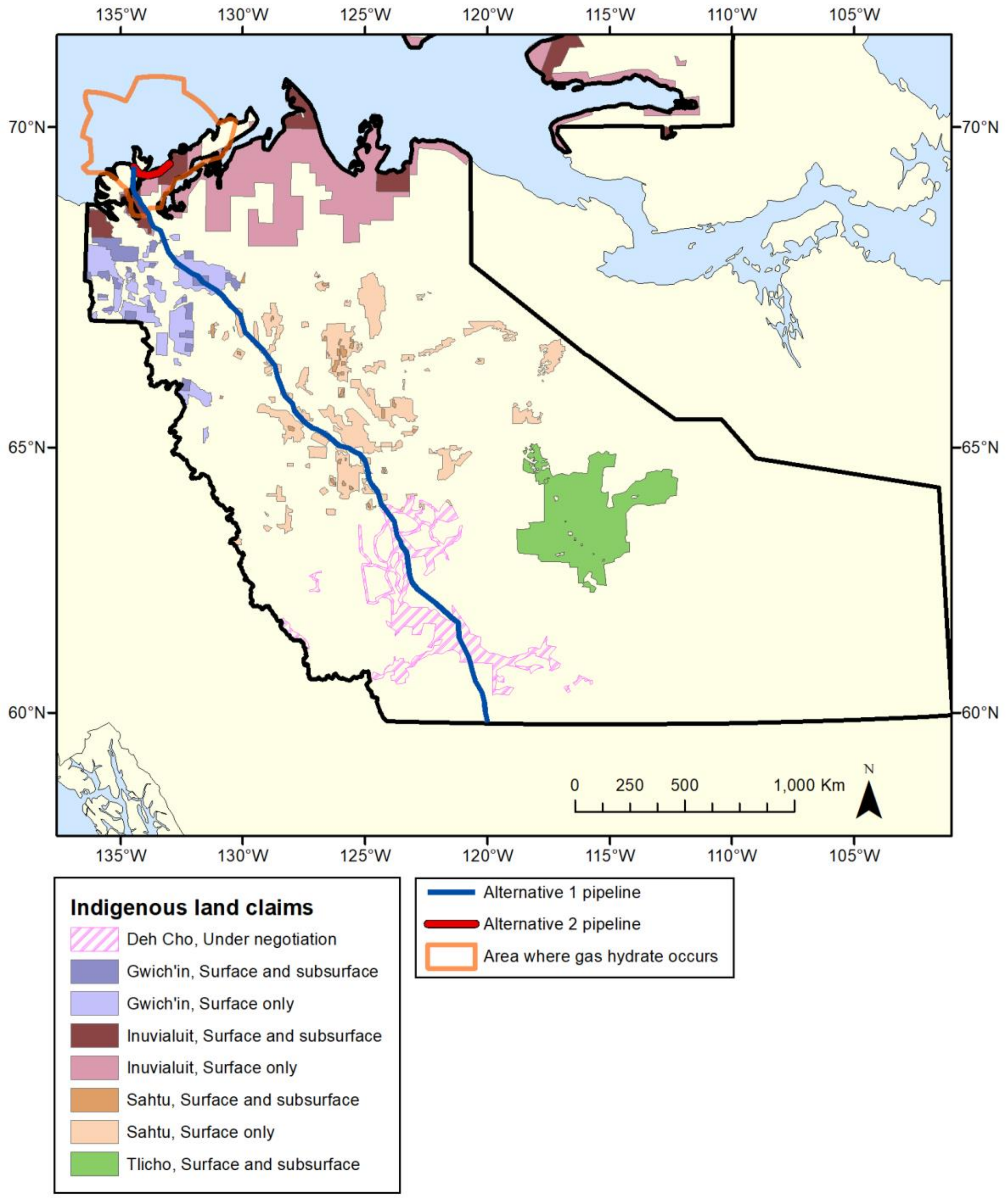


Figure 5.3 *Title lands for the potentially impacted indigenous groups within the Northwest Territories (black outline) overlain by alternative pipeline routes (Aboriginal Affairs and Northern Development Canada, 2012).*

The Inuvialuit land claim was designed with the aim of them dictating economic development in their region, while also preserving the productivity of that environment, creating two opposing mandates (Elias, 1995). The Inuvialuit own much of Northwest Territories coastline, including the potential hydrate field area, where the Inuvialuit have subsurface land rights to 2600 km^2 and surface land rights to 4650 km^2. Subsurface rights are necessary to exploit any underground resource, such as gas hydrate, so are also relevant on Inuvialuit lands. The Inuvialuit claim amounts to roughly 7% of the subsurface area and 14% of the surface area where gas hydrate is predicted to occur, but this land would be preferred for development to other areas of the stability field, as it is onshore with existing road infrastructure, whereas the remaining hydrate area is offshore, or in industrially undeveloped areas onshore.

The Gwich'in signed a land claim agreement in 1992 to surface ownership over 22,422 km^2 of the northern Mackenzie Valley, with subsurface rights to 27% of this land (Meis Mason et al., 2012). Most Gwich'in land is west of the proposed pipeline route, but the pipeline would pass through lands with Gwich'in surface rights south-east of Inuvik. Gwich'in land ownership protects the hunting use of the land, while entitling them to royalties on any infrastructure development, so the two competing land uses would again have to be balanced (Meis Mason et al., 2012).

The Sahtu claim many small separated parcels of land, as the Sahtu agreement focussed on surface rights in areas traditionally used for hunting and trapping (Dokis, 2010). Decisions on land use are dictated by a Sahtu corporation, a group split between those looking to maximise financial returns from industry and those looking to preserve land for hunting (Dokis, 2010). As the pipeline route would cross many areas where the Sahtu have surface rights, there may be complicated disputes over individual parcels of land unless a general agreement is made with Sahtu leadership.

The Deh Cho land claim is not yet settled, but remains potentially significant for pipeline development. The Deh Cho claim covers the southern Mackenzie River corridor and tributaries, and the proposed pipeline follows the river valley (Meis Mason et al., 2012). An interim agreement with the Deh Cho suggested 50% of the claimed land be preserved, and 50% left open to oil and gas development, as well as establishing formal bodies to negotiate oil and gas royalties on behalf of affected communities (Meis Mason et al., 2012). Therefore, the Deh Cho may be willing to allow surface pipeline development, if sufficient area is preserved for other use. As unresolved land disputes have prevented industrial development proposals before (Berger, 1977), this incomplete agreement may provide the most significant issues for any project.

In alternative 2, the well would not be sited on Inuvialuit land, but to connect gas production to Tuktoyaktuk would require routing a pipeline over land where the Inuvialuit hold surface and subsurface rights. The population of Tuktoyaktuk, who would benefit from the industrial development, is predominantly Inuvialuit (Andrachuk and Pearce, 2010), and so they may be willing to allow this development in exchange for the gas supply.

There are many environmental designations in the Northwest Territories, originating from national and regional governance (Figure 5.4). Some of these are not relevant; there are few National Parks in the Northwest Territories (Blake, 2019; Stadel et al., 2002), none of these intersect the pipeline route. There are also two National Historic Sites, both of which are north of the proposed pipeline route (Aboriginal Affairs and Northern Development Canada, 2012).

The gas hydrate field overlaps 370 km^2 of Kendall Island Migratory Bird Sanctuary and 660 km^2 of offshore marine protected areas. Kendall Island provides seasonal breeding grounds for migratory shorebirds (Pirie et al., 2009), and the marine protected areas are habitats for migratory shorebirds and fish, both with a primary purpose of conservation, irrespective of economic development (Guénette and Alder, 2007). Opposition to industrial development in either of these areas will reduce the total producibility of the field, and may make it difficult to connect pipeline infrastructure. As in Alaska, environmental opposition includes regional programs of many large multi-national organisations (e.g. Greenpeace, International Boreal Conservation Campaign, Natural Resources Defence Council, Sierra Club and WWF) and elements of the indigenous population (Ridgeway, 2007).

The Gwich'in have developed a comprehensive development plan for their lands to balance resource development and environmental conservation, as they are aware of the potential significance of their lands to any gas pipeline from the Mackenzie Delta (Simpson et al., 2015). The main distinction is between: Gwich'in general land use zones, where land use is permitted subject to general laws; Gwich'in special management zones, where new development has to pass stricter conditions that address concerns of local communities; and Gwich'in conservation zones, where oil and gas exploration and other extractive industry is not permitted, although a pipeline is permitted if there is no viable alternative route (Simpson et al., 2015). 16 km^2 of special management zones will be impacted in the Campbell Hills and around Travaillant Lake, while Travaillant Lake is a conservation zone. The shape of the conservation zone, and nearby settlement of Tsiigehtchic, justify this pipeline route, as a long diversion would be necessary to avoid the conservation zone entirely (Simpson et al., 2015). The pipeline route also passes close to Gwich'in Territorial Park, which has been established by the Northwest Territories government for recreation and as a wildlife habitat (Simpson et al., 2015), where development permission would be unlikely.

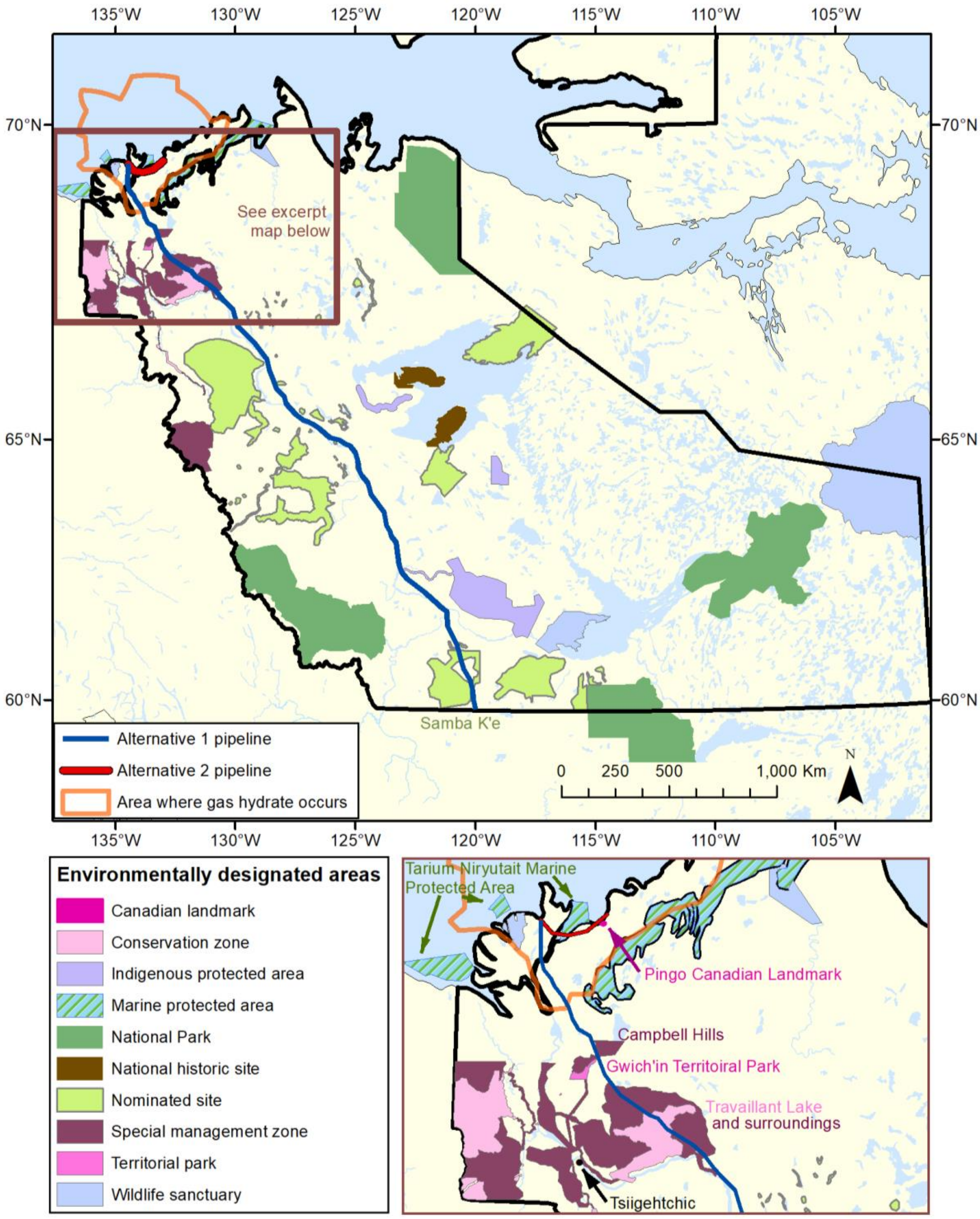


Figure 5.4 *Lands with a conservation status or other restriction placed on development within the Northwest Territories (black outline) overlain by alternative pipeline routes (Aboriginal Affairs and Northern Development Canada, 2012), with an excerpt showing more detail at the pipeline north end. Bodies of water are shown in blue.*

Communities along the length of the Mackenzie River have nominated additional conservation areas as essential for maintaining their economies and cultures (Stadel et al., 2002). Although these areas have no formal status, as they have been identified as important by local communities there would likely be opposition to these areas being developed industrially. The largest proposed area on the pipeline route is Sambaa K'e (Trout Lake). This lake has had temporary environmental protection from development before, and development could be restricted here again (Burrowes, 2013). Overall 9 km^2 of the pipeline footprint is through suggested conservation areas.

Connecting Mallik to Tuktoyaktuk would be difficult despite the short distance, as much of the route has some environmental protection. Near Tuktoyaktuk is Pingo Canadian Landmark, where 8 of the pingos common on the Tuktoyaktuk peninsula are protected as representative of the landscape (Mackay, 1998). An offshore route to avoid this landmark would then impact Tarium Niryutait Marine Protected Area, which is managed to protect local subsistence stocks of beluga whales (Fisheries and Oceans Canada, 2009). The final pipeline route is diverted south of the most direct route to minimise environmental objections, although this increases length and cost.

5.2.3 Weighting

As I did not approach real-world stakeholders in this region, I used three different hypothetical weighting schemes, following my experience in Alaska, to represent the likely range of opinions on the topic, and explore how different sets of criteria weights affect the final decision. The base case weighing scheme gave equal weight to each top level criterion, providing a neutral position on the decision. As I used different numbers of criteria beneath each top-level criterion, the weight of each individual criterion differs (

Table **5.2**). I used two further weighting schemes, based upon the two stakeholder positions I encountered in Alaska (Section 4.4), one allocating 75% of total weight to resource and economic criteria, the other allocating over 75% of total decision weight to social and environmental criteria. I set my hypothetical weighting schemes from the range of weighting that I encountered in Alaska (the most extreme stakeholder weights had 84% social/environmental weight and 63% economic/resource weight), to explore the full range of possible results. The range of weights used present end member scenarios to test the protocol computes distinct results.

Table 5.2 *Criteria weighting schemes used to represent hypothetical stakeholder priorities at the Mackenzie Delta.*

	Homogenous weights	*Resource/Economic prioritised*	*Environmental/ Social prioritised*
Gas (m^3/day)	3	5	1
Cost ($CAN million)	1.5	5	1
Cost of living (reduction in electricity cost)	1.5	5	1
Employment (persons)	1	1	1.8
Migration (persons)	1	1	1.8
Subsistence	1	1	1.8
Pollution (m^3/day)	1.5	1	1.8
Land Take (km^2)	1.5	1	1.8
Weight percentages			
Resource & Economic	50	**75**	25
Social & Environmental	50	25	**75**

5.2.4 Thresholds

The ELECTRE method used in my protocol requires three thresholds to be defined for each criterion, indifference (I), preference (P) and veto (V) (Figueira et al., 2013). The indifference threshold represents the minimum difference in performance between two alternatives necessary for them to be distinguishable. In my study this corresponds to the largest error margin on any alternative, as below this value any differences in performance between alternatives can be explained by measurement error. The preference threshold is the lowest difference between two alternatives for one to be strongly preferred to the other. If the difference between two alternatives is greater than the indifference threshold, but below the preference threshold, a weak preference exists (Figure 5.5), as one alternative will have measurably better performance, but not sufficiently superior performance for one alternative to be strongly preferred. The veto threshold prevents one alternative outranking another if the alternative that would outrank the other is inferior in performance by the veto threshold or more. This threshold prevents the protocol recommending a generally superior alternative that has significantly inferior performance for a small number of criteria.

I used a range of hypothetical thresholds to explore this decision space, as I did not approach stakeholders who could supply individual thresholds. Indifference thresholds (Table 5.3) are fixed at the reported or calculated error margins for the impact estimates presented in Table 5.1. Preference thresholds were varied from minimum values close or equal to indifference thresholds, to maximum values sufficient to cover the value range of all alternatives (Table 5.3). I have measured subsistence qualitatively, with subsistence impact assigned one of eight increasing categorical descriptions (none, very low, low, rather low, moderate, rather high, high, and very high). These categorical descriptions were used to cover value ranges, averaging the impact on multiple species, where a single numerical value has little meaning (World Health Organization and Food and Agriculture Organization of the United Nations, 2009). The category values are a standard ordinal rating scale (Trochim et al., 2016). As such, indifference, preference and veto thresholds on this criterion are given as a number of categories difference in performance between two alternatives. For example, an indifference threshold of one category would mean that a pair of alternatives with impact differing by one category (e.g. very low & low or moderate & rather high etc.) would be evaluated as equivalent. Therefore, the maximum threshold on this criterion is seven categories, the difference between “none” impact and “very high” impact.

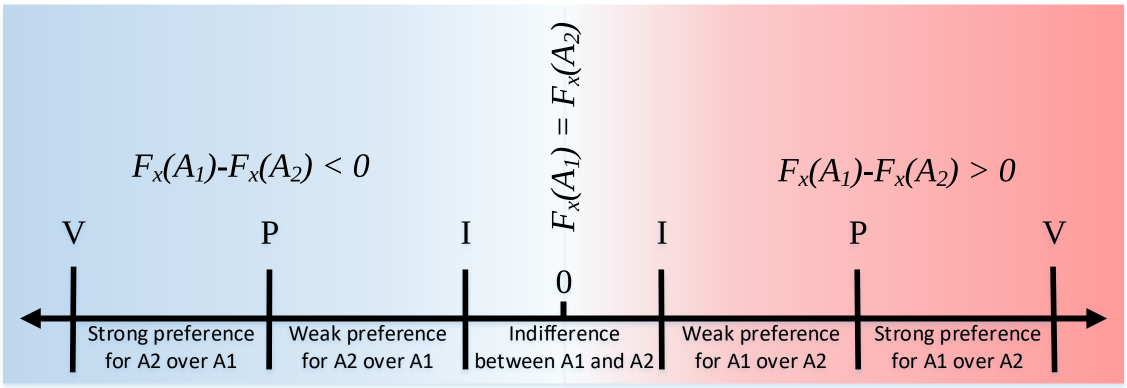


Figure 5.5 *Resultant preference for a range of differences in performance between two alternatives ($F(A_1)$ & $F(A_2)$) on a single criterion, x, where higher values are preferred. I, indifference threshold; P, preference threshold; V, veto threshold.*

I explored how different preference relationships between alternatives on each criterion, and combinations thereof, impacted the final decision. All possible combinations of the thresholds in Table 5.3 were simulated using MCDA-ULaval software (Abi-Zeid et al., 2015) to identify which criteria have discriminatory power over the final decision (mathematical formulation of the method is presented in Section 2.3). Each threshold combination was simulated for each of the three weighting schemes (

Table **5.2**), resulting in three sets of 20736 scenarios. When simulating for preference thresholds, veto thresholds were omitted.

Table 5.3 *Indifference thresholds (I) and range of preference thresholds (P) used with the impact matrix (Table 4.1) for ELECTRE III scenario analysis without veto threshold at the Mackenzie Delta. Direction of preference indicates whether higher or lower values are preferred for each criterion.*

		Indifference	Preference	Direction of preference
Resource	Gas (m^3/day)	$3x10^6$	[$3x10^6$, 6 $x10^6$, 9 $x10^6$, 1.2 $x10^7$]	Maximise
Economic	Cost ($CAN million)	500	[1000, 5000, 9000, 13000]	Minimise
	Cost of living (reduction in electricity cost)	17%	[20%, 40%, 60%]	Maximise
Social	Employment (persons)	200	[400, 800, 1200]	Maximise
	Migration (persons)	400	[400, 800, 1200]	Minimise
	Subsistence	1 category	[1, 3, 5, 7] categories	Minimise
Environmental	Pollution (m^3/day)	10000	[10000, 20000, 30000]	Minimise
	Land Take (km^2)	300	[500, 2500, 4500, 6500]	Minimise

I tested the impact of using a veto threshold by setting the preference threshold equal to the indifference threshold (P=I), then varying the veto thresholds over the remaining range of indifference threshold values (Table 5.3). As a result, I ran 1296 scenarios for each of the three weighting schemes (

Table **5.2**), covering all combinations of veto thresholds. I also simulated with P=I for all criteria, with no veto thresholds, to act as a comparative control to establish the impact of the thresholds. I did not simulate scenarios where preference and veto thresholds varied simultaneously due to computational limitations.

The consequences of each preference threshold value, broken down by criteria, are shown in Table 5.5. For example, the values for gas production for each alternative are; alternative 1 = $1x10^7$ m^3/day, alternative 2 = $1x10^5$ m^3/day and alternative 3 = 0 m^3/day (Table 5.1). The indifference threshold for this criterion is $1x10^6$ m^3/day (Table 5.3), and the difference between alternatives 2 and 3 in performance ($1x10^5$ m^3/day) is below this value, so there is indifference between these alternatives on this criterion at all threshold values (Table 5.5). The difference between alternative 1 and alternative 2 (≈$1x10^7$ m^3/day) is above preference threshold values of $3x10^6$ m^3/day, $6x10^6$ m^3/day or $9x10^6$ m^3/day, which are the minimum differences in performance for strong preference for one alternative over another. As higher performance is preferred on this criterion, alternative 1 is strongly preferred to alternative 2 (Table 5.5). At a preference threshold of $1.2x10^7$ m^3/day, the difference between alternatives 1 and 2 (≈$1x10^7$ m^3/day) is no longer greater than the preference threshold, but it is still greater than the indifference threshold, so the alternatives can be discriminated, meaning there is a weak preference in favour of alternative 1.

Simulating preference scenarios for all threshold values results in multiple different alternative rankings for each weighting scheme. I identify trends in these rankings to determine which criteria or specific threshold values cause discrimination between end results.

Table 5.4 *Indifference (I), preference (P) and veto (v) threshold values used alongside the impact matrix (Table 5.1) for veto threshold scenario analysis at the Mackenzie Delta.*

		Indifference	Preference	Veto
Resource	Gas (m^3/day)	$3x10^6$	$3x10^6$	[$6x10^6$, $9x10^6$, $1.2x10^6$]
Economic	Cost ($CAN million)	500	500	[5000, 9000, 13000]
	Cost of living (reduction in electricity cost)	17%	17%	[40%, 60%]
Social	Employment (persons)	200	200	[800, 1200]
	Migration (persons)	400	400	[800, 1200]
	Subsistence	1 category	1 category	[3, 5, 7] categories
Environmental	Pollution (m^3/day)	10000	10000	[20000, 30000]
	Land Take (km^2)	300	300	[2500, 4500, 6500]

Table 5.5 *Summary of implications of all threshold values on the relationship between each alternative pair – whether a strong preference (S), weak preference (W) or indifference (I) (Figure 5.5) results on that criterion alone. aSb indicates alternative a is strongly preferred to alternative b.*

Preference thresholds	Alternatives 1 & 2	Alternatives 1 & 3	Alternatives 2 & 3
Gas (m^3/day)			
$3x10^6$	1**S**2	1**S**3	**I**
$6x10^6$	1**S**2	1**S**3	**I**
$9x10^6$	1**S**2	1**S**3	**I**
$1.2x10^7$	1**W**2	1**W**3	**I**
Cost ($CAN million)			
1000	2**S**1	3**S**1	**I**
5000	2**S**1	3**S**1	**I**
9000	2**S**1	3**S**1	**I**
13000	2**W**1	3**W**1	**I**
Cost of Living (% reduction)			
20	**I**	1**S**3	2**S**3
40	**I**	1**W**3	2**W**3
60	**I**	1**W**3	2**W**3
Employment (persons)			
400	1**S**2	1**S**3	**I**
800	1**W**2	1**W**3	**I**
1200	1**W**2	1**W**3	**I**
Migration (persons)			
400	2**S**1	3**S**1	**I**
800	2**W**1	3**W**1	**I**
1200	2**W**1	3**W**1	**I**
Subsistence (categories)			
1	2**S**1	3**S**1	3**S**2
3	2**W**1	3**S**1	3**S**2
5	2**W**1	3**S**1	3**W**2
7	2**W**1	3**W**1	3**W**2
Pollution (m^3/day)			
10000	2**S**1	3**S**1	**I**
20000	2**W**1	3**W**1	**I**
30000	2**W**1	3**W**1	**I**
Land take (km^2)			

500	2**S**1	3**S**1	**I**
2500	2**S**1	3**S**1	**I**
4500	2**S**1	3**S**1	**I**
6500	2**W**1	3**W**1	**I**

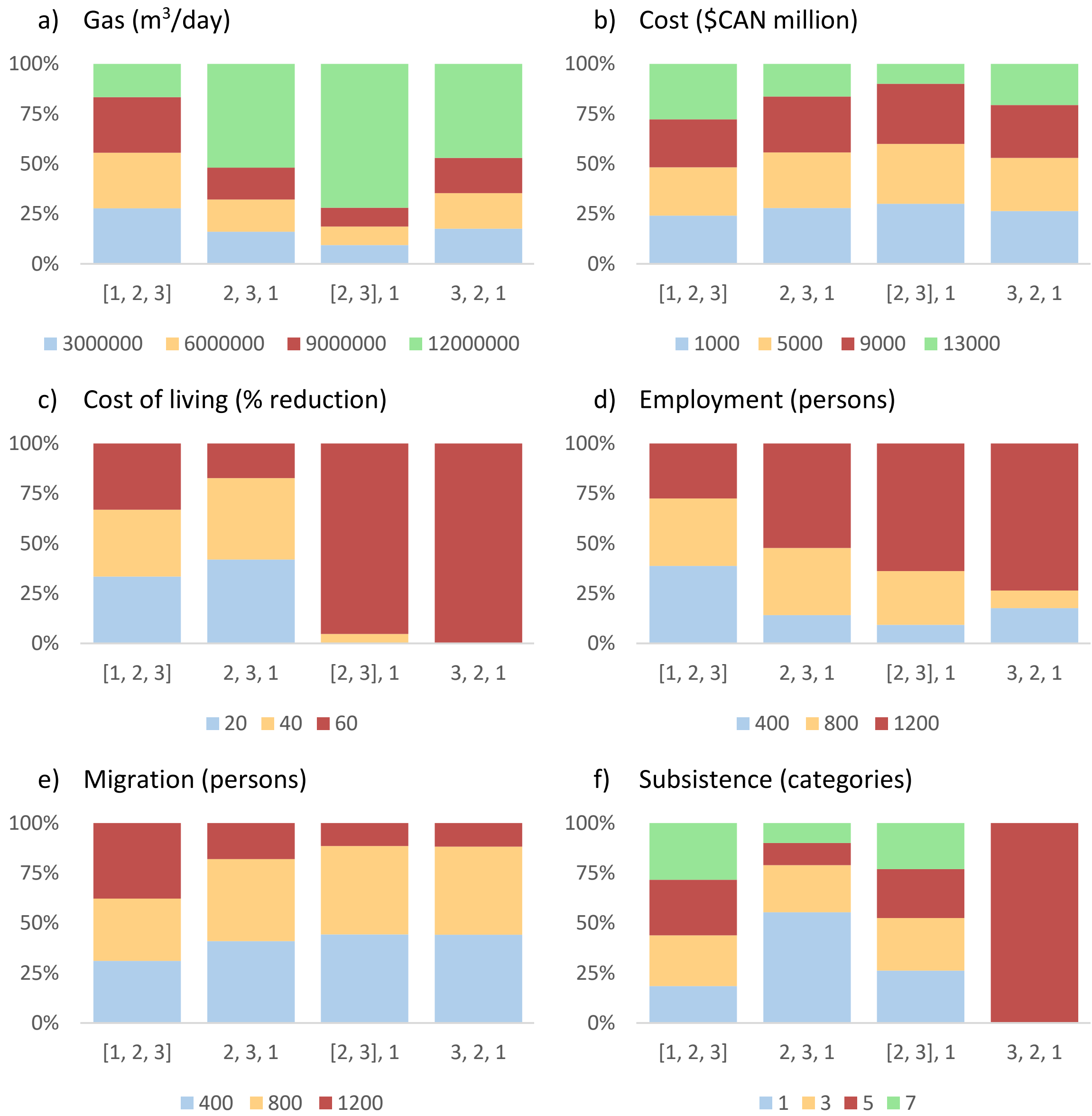
5.2.5 Results

To establish the effects of different preference threshold values I compared the relative distribution of preference threshold values in scenarios resulting in each different alternative ranking (Figure 5.6-Figure 5.8). If the value of a preference threshold impacts the result it will have an irregular distribution, signifying that some rankings only result for certain threshold values. I explore which results are possible for each weighting simulation (Table 5.6), but do not consider relative frequency of results, which is influenced by the values chosen for simulation.

With the homogenous weighting scheme, it is possible for all alternatives to be ranked equally (Table 5.6). Where a rank order develops, alternative 1 is always outranked by the remaining two alternatives (Table 5.6). The result of alternative 3 ranked first, followed by alternative 2, then alternative 1, only occurs in a small range of preference threshold values (Figure 5.6), with other results covering larger preference threshold ranges. Gas is the only resource criterion, and so has higher weight than any other individual criterion in a homogenous weighting scheme (

Table **5.2**), so the preference relationship on this criterion controls the overall rank order (Figure 5.6a). For example, P(gas) = 1.2×10^{7} m^3/day is the only preference threshold for gas where there is only weak preference for alternative 1 (Table 5.5), allowing alternative 1 to be outranked overall (Figure 5.6). Outranking of alternative 1 is more common in scenarios with high preference thresholds for employment and low preference thresholds for migration or pollution (Figure 5.6d, e, g), as these values lead to strong preferences against alternative 1, and only weak preferences at best for alternative 1.

With most weight given to resource and economic criteria, four distinct rankings develop (Table 5.6), all of which have alternative 2 ranked first or equal first, including the result of all alternatives ranked equally. Alternative 1 outranking or equivalent to alternative 3 requires P(cost of living) = 20% (Figure 5.7c), as this criterion has high weight, and this value creates a strong preference for both alternatives over alternative 3 (Table 5.5). Even with this strong preference for alternative 1 on cost of living, P(employment) = 1200 persons or P(subsistence) = 1 or 3 categories results in alternative 1 and 3 ranking equally (Figure 5.7d, f). Alternative 3 outranks alternative 1 due to P(gas) = 1.2×10^7 m^3/day as in the uniform weight scenarios, and high preference thresholds for cost of living and employment (Figure 5.7c, d). At these values, alternative 1 is only weakly preferred on criteria where it has positive performance (Table 5.5) and is outranked overall due to its performance on the remaining criteria.



g) Pollution (m^3/day)

h) Land take (km^2)

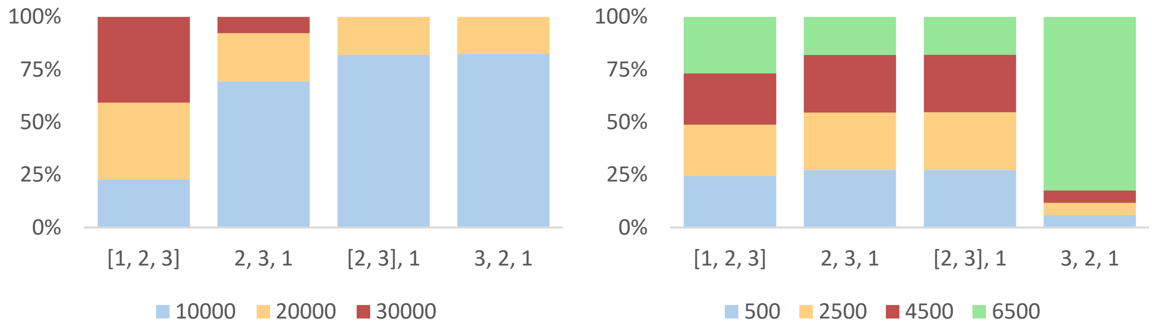
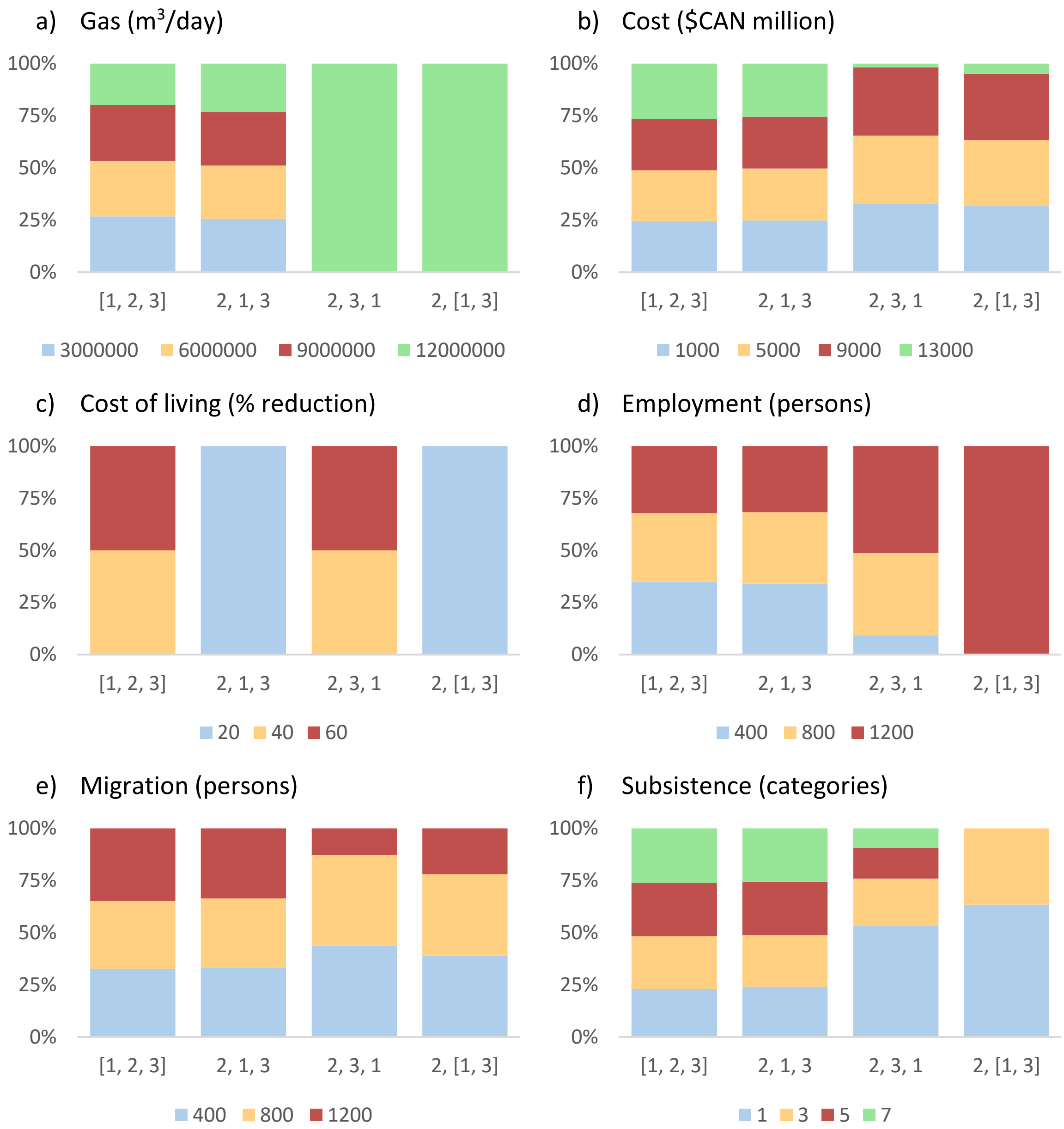


Figure 5.6 *Summary of scenario results with the uniform weighting scheme over range of preference thresholds for each criterion. Each panel shows the breakdown of criterion thresholds resulting in each alternative ranking as a percentage of all scenarios.*



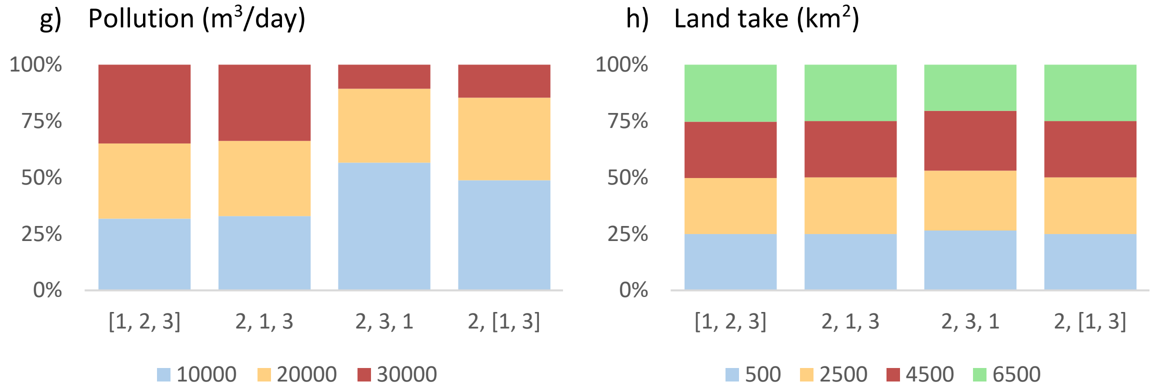
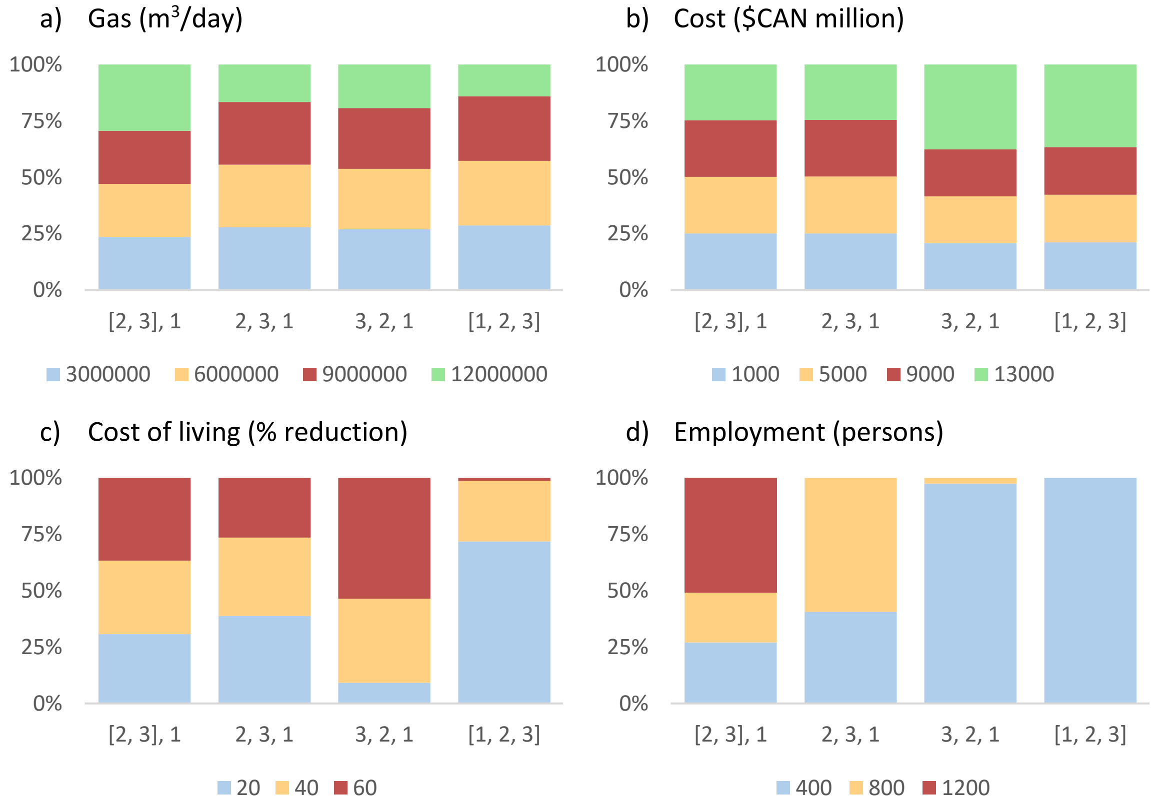


Figure 5.7 *Summary of scenario results with the resource/economic weighting scheme over range of preference thresholds for each criterion. Each panel shows the breakdown of criterion thresholds resulting in each alternative ranking as a percentage of all scenarios.*



e) Migration (persons)

f) Subsistence (categories)

Figure 5.8 *Summary of scenario results with the social/environmental weighting scheme over range of preference thresholds for each criterion. Each panel shows the breakdown of criterion thresholds resulting in each alternative ranking as a percentage of all scenarios.*

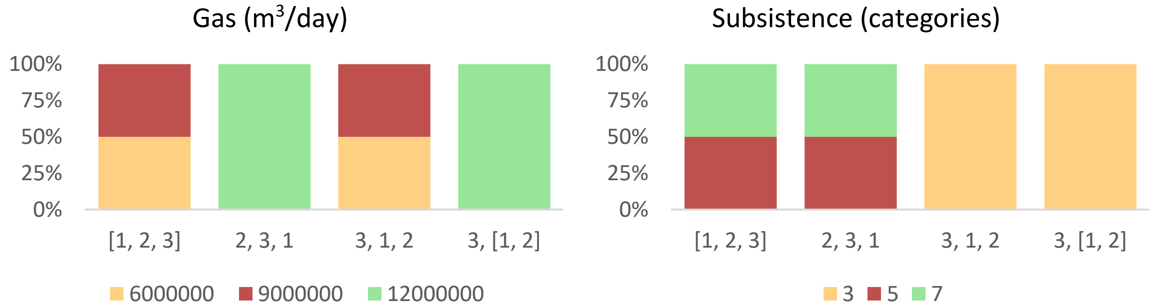
In the high social and environmental weight scenarios, alternative 1 is always outranked, except for scenarios where all alternatives rank equally (Table 5.6). The remaining results are different rank orders of the remaining alternatives. Employment is the only social or environmental criterion where alternative 1 outperforms the other alternatives (Table 5.5), but alternative 1 can still be outranked in some cases with P(employment) = 400 (Figure 5.8d). As the difference in performance of alternatives 2 and 3 is below the indifference threshold for most criteria, they are generally ranked equal. Cost of living influences the end result despite having low weight in these scenarios as it differentiates between alternatives 2 and 3. Alternative 3 is more commonly ranked first at high preference thresholds on this criterion (Figure 5.8c), since both other alternatives are strongly preferred at lower threshold values (Table 5.5). Alternative 3 only outranks both alternatives under a narrow range of preference thresholds (Figure 5.8), where alternative 2 can be outranked due to the preference for alternative 3 on the subsistence criterion.

Table 5.6 *Matrix showing possible results for each weighting scheme (orange ticked), with white crosses indicating a result that did not occur for any threshold values with the specified weighting. Each column representing one set of scenarios. Square brackets indicate alternatives are equally ranked. Rankings that did not result from any scenario are not shown.*

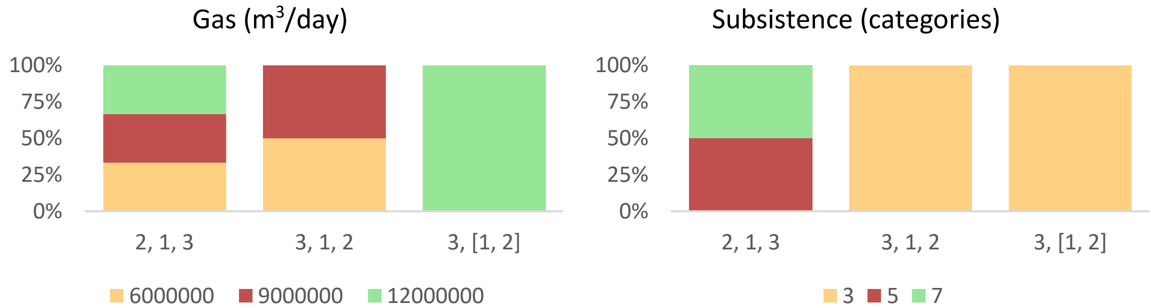
		Preference scenarios			Veto scenarios		
Weighting Scheme		Uniform	Res/Econ	Soc/Env	Uniform	Res/Econ	Soc/Env
Possible alternative rankings	*[1,2,3]*	✓	✓	✓	✓	×	✓
	[2,3], 1	✓	×	✓	×	×	×
	2, [1,3]	×	✓	×	×	×	×
	3, [1,2]	×	×	×	✓	✓	×
	2, 1, 3	×	✓	×	×	✓	×
	2, 3, 1	✓	✓	✓	✓	×	✓
	3, 1, 2	×	×	×	✓	✓	✓
	3, 2, 1	✓	×	✓	×	×	✓

Introducing veto thresholds has a similar impacts on the final result, irrespective of the weighting scheme used. In most scenarios my chosen veto thresholds did not affect the final result, which was instead caused by the preference thresholds and criteria weights. In many cases veto thresholds would prevent alternative 1 from outranking other alternatives, but this alternative was already last ranked due to the preference thresholds. The only criteria where a veto threshold affected the final result were gas production and subsistence. In gas production, low values for the veto threshold cause alternative 1 to rank equal to the other alternatives, or to outrank alternative 2 (Table 5.6). Subsistence veto thresholds prevent other alternatives from outranking alternative 3, resulting in alternative 3 ranked first in all scenarios with V(subsistence) = 3 categories (Figure 5.9).

a) Homogeneous weight scheme



b) Resource/Economic weight scheme



c) Social/Environmental weight scheme

Gas (m^3/day) Subsistence (categories)

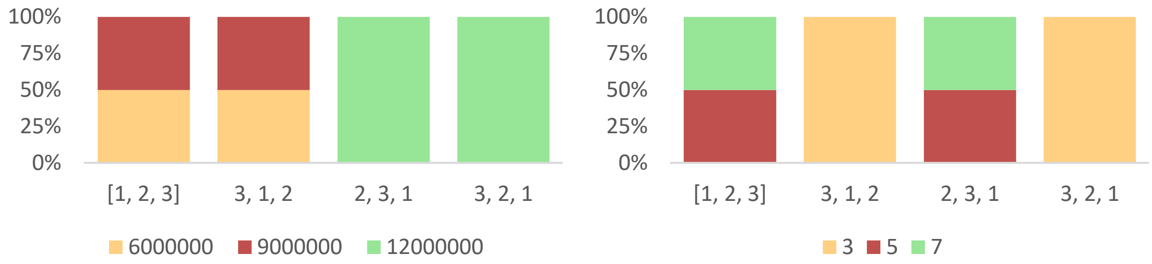


Figure 5.9 *Summary of scenario results for veto thresholds for each weighting scheme. Only criteria where thresholds discriminate between results are shown.*

5.2.6 Discussion

Throughout all scenarios, alternative 1 is never ranked as the sole preferred alternative. For the criteria included here, alternative 1 only performs positively on gas production, cost of living and employment. Even with a resource/economic focus, the high cost of alternative 1 prevents it from ranking first, although it does outrank alternative 3 in 32.5% of scenarios. Cost of living as I have measured it does not capture that many more people could receive this benefit from a large pipeline development, compared to a development only supplying Tuktoyaktuk. As a result, alternative 1 is not discriminated from alterative 2 by this criterion in my study. Considering benefit distribution (Adler, 2012) may cause a more favourable view of alternative 1, although its negative social and environmental impacts would be distributed across an equally wide area.

Although my protocol evaluates alternative 2 generally favourably, this assessment is not comprehensive, and there are limitations to the alternative that may reduce its viability. Alternative 2 requires high capital investment for a very small market, likely necessitating government financing, as it is unlikely to be considered an attractive commercial opportunity. The government has recently invested into infrastructure for small communities including Tuktoyaktuk (Bennett, 2018), and may be willing to again, especially as it currently subsidises high energy costs that could be reduced by this development. However, government opinion may not support this development, following the failure of other regional conventional gas projects, that had high costs for a much smaller resource return than anticipated (CBC News, 2011b). It should also be noted that there are conventional gas resources in the Mackenzie Delta region that could equally be developed (Gibson, 2011), and probably at less cost than the gas hydrate. Finally, governmental commitments towards cleaner energy and limiting coastal Arctic development may hinder any regional gas project, conventional or unconventional (Shapovalova and Stephen, 2019), although the Northwest Territories has the least aggressive targets of any Canadian province (Fertel et al., 2013). Canada has invested in hydroelectric power, and could implement this power generation on the Mackenzie River (Liming et al., 2008). Rural communities have interest in multiple small scale renewable power generation mechanisms, for reliable and clean energy generation, such as solar, micro hydro-electric or biomass generation (St. Denis and Parker, 2009). Although equally expensive, these energy production mechanisms create less environmental damage, and may be more sustainable and supported in rural communities, where the government may be willing to subsidise development costs (Basbous et al., 2015). This additional detail shows the importance of contextualising the results whenever the protocol is used, and also considering the initial condition, the fourth element of my protocol (Figure 5.10), when defining reasonable alternatives.

Alternative 2 can lose its rank position by introducing a veto on subsistence impact. Since I have not spoken to Canadian stakeholders, it is difficult to say how likely this threshold is, as local communities participate in a mixed subsistence and wage economy (Nuttall, 2008). In Alaska there was an upper limit on how much damage is acceptable to the subsistence system, but the some parts of community would support industrial development if they can participate in the resulting economic opportunities. Vetoes are not purely designed to restrict development however, and vetoes on gas production can stop industrial development if insufficient gas is produced, necessitating larger development to pass the veto threshold. In these scenarios this veto can result in alternative 1 outranking alternative 2.

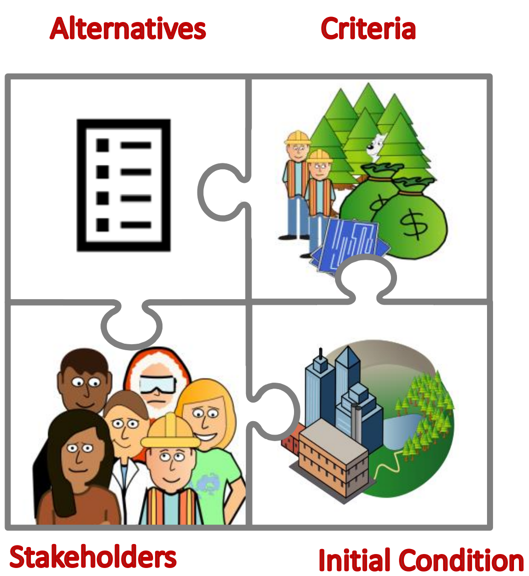


Figure 5.10 *Summary of four necessary components for evaluation using my protocol.*

As I limited the criteria used, my case study is less comprehensive than ultimately possible. In most cases criteria were omitted due to a lack of data for this site, or for commercial gas hydrate operations in general, but some omitted criteria may alter the final results, if included in a future assessment. In particular, alternative 1 could become more viable if there was a large government impetus for this development, which would be included by evaluating taxation (F5) and legislation (I1). In Canada, the government is committed to reducing fossil fuel use and offshore development (Shapovalova and Stephen, 2019), so including legislation may actually count against the development alternatives here. Taxation revenue could improve the economics of alternative 1, which is currently hindered by high development costs, but it is unlikely the effects of this criterion alone would mitigate the negative social and environmental consequences of alternative 1 sufficiently for it to become recommended. Another potentially significant omission is unintended environmental impacts (E5), as Arctic environments are highly fragile and slow to recover once polluted, and species are often concentrated in small areas that could be erased in a single spill (Gulas et al., 2017). This criterion would further count against alternative 1, but may also oppose the development of alternative 2.

5.2.7 Conclusions

Unlike Alaska, the Mackenzie Delta has not experienced resource development, so gas hydrate could be developed here to provide revenue for the territory or as an energy source for isolated communities. Mackenzie Valley pipeline proposals have proven controversial before as the gas supply has never proven sufficient to justify the large cost, environmental consequences and societal disruption of the development, so this protocol could be used to explore if a balance can be found when developing gas hydrate here.

5.3 Messoyakha Field, Russia

The Messoyakha gas field is located at the eastern edge of the Yamalo-Nenets Autonomous Okrug (YNAO, Figure 5.11). It was the first commercial gas field in this region, beginning production in 1969 (Collett and Ginsburg, 1998), and production continues today (Makogon and Omelchenko, 2013) with the gas supplied to heavy industry in Norilsk by pipeline (Makogon, 2012). Like many west Siberian gas fields, Messoyakha is operated by Gazprom, a major public company majority owned by the Russian government (Yakushev and Chuvilin, 2000). Gazprom operates 18% of global natural gas reserves, accounting for 75% of the Russian domestic market; is the primary operator of the Unified Gas Supply System, a 632,000 km pipeline network connecting the main Russian gas fields with eastern Europe and west Asia (Figure 5.11); and is the sole exporter of natural gas from Russia (Vavilov and Nicholls, 2015). The Messoyakha field is currently producing small volumes of gas, around 3.5 Bcf/yr (Makogon and Omelchenko, 2013), compared to production in the regional giant and supergiant fields that can exceed 350 Bcf/yr (Söderbergh et al., 2010). Present-day production is well below the historical peak for the field, as only four wells remain operational compared to 45 wells at its height (Makogon and Omelchenko, 2013).

Because gas hydrate has not been directly sampled at Messoyakha, its presence and contribution to gas production have both been subject to debate (Collett and Ginsburg, 1998). Gas hydrate was suggested as pressure and temperature conditions of the reservoir are suitable for hydrate stability (Makogon et al., 1972). Further evidence used to support the potential presence of gas hydrates is: no change in the gas-water contact over the production lifespan of the field; wells in the presumed gas hydrate bearing layer having relatively low flow rates until the addition of a methanol inhibitor; and a measured pressure increase during well shut-in, taken as gas hydrate derived gas recharging the reservoir (Grover et al., 2008). The argument against gas hydrate contributing to production centres on elevated helium concentrations in the produced gas, although this variation may not be directly linked to the presence or absence of hydrate (Collett and Ginsburg, 1998). Additionally, water production at the surface is lower than expected if gas hydrate is dissociating, but this discrepancy may be explained by produced water remaining in the formation (Makogon and Omelchenko, 2013). I proceed assuming gas hydrate is present within the field.

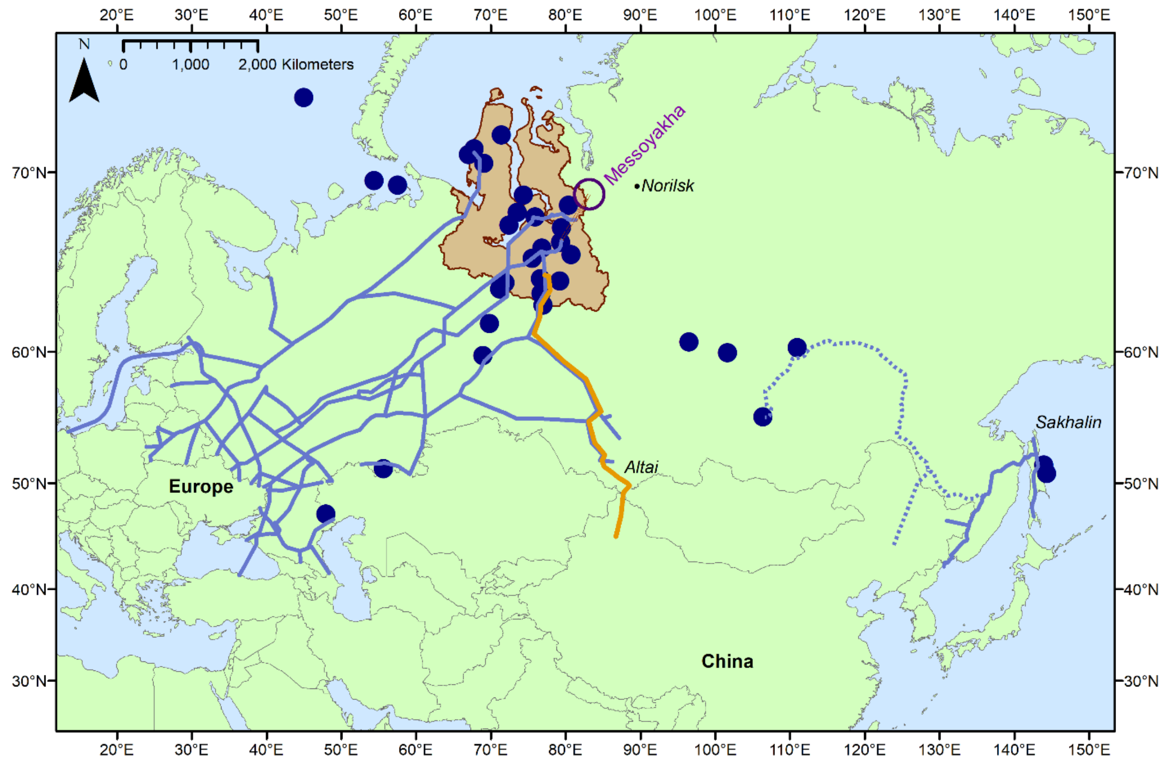


Figure 5.11 *Map showing active Russian fields (navy dots), Messoyakha field (purple; Krason and Ciesnik, 1985) the Unified Gas Supply System (blue line), including sections under construction (blue dashed line), planned Altai pipeline route (gold) and the Yamalo-Nenets Autonomous Okrug (orange). Other smaller pipelines for local distribution are not shown for clarity, but Norilsk is already connected to the Messoyakha field.*

5.3.1 Gas Hydrate at Messoyakha

The Messoyakha field is believed to have a gas hydrate layer from 730 m to 805 m depth, with free gas below, both within the same permeable strata (Makogon, 2010). The precise depth to the gas hydrate/free gas contact is not known (Makogon and Omelchenko, 2013). Gas hydrate saturation is estimated between 20-50% (Adzynova and Sukhonosenko, 2010). As of 2011, total gas in place at Messoyakha was estimated at 0.82 Tcf, including up to 0.24 Tcf as gas hydrate (Makogon and Omelchenko, 2013), around 0.05% of total Russian gas reserves (Nazarov, 2015). As reservoir pressure has remained constant since 1975 (Collett and Ginsburg, 1998), hydrate-derived gas is believed to be maintaining reservoir pressure (Makogon and Omelchenko, 2013). I estimate present day total gas in place at 0.79 Tcf, of which around 0.23 Tcf remains in solid hydrate form, as it is estimated that around 40% of the gas produced at the field is gas hydrate derived (Makogon and Omelchenko, 2013). Current production wells are drilled through gas hydrate bearing strata, and in some instances have unintentionally attempted to produce from these layers, resulting in very low gas flow (Makogon and Omelchenko, 2013). Commercial gas production from hydrates would use depressurisation in vertical wells (Makogon and Omelchenko, 2013). In addition to depressurisation, chemical inhibitors would be used to aid initial destabilisation in the immediate well area (Grover et al., 2008). Based upon previous experience from inhibitor treatment, best estimates of potential future production rates are 1230 MMcf per well per year (Chistyakov, 2009).

5.3.2 Alternatives

Unlike my other case studies, gas hydrate development at Messoyakha is not needed to meet a market gap in gas supply; Russia's export potential for natural gas exceeds demand (Paltsev, 2014). However, as this field has been industrialised, with infrastructure connections to Russia's Unified Gas Supply System, Russia could intensify production at this field by targeting the gas hydrate layer, focusing development costs and returns in the near future, rather than gambling on long-term uncertainty. If the world continues to transition away from carbon based fuels, undeveloped resources may become unusable later in the century (Arent et al., 2011). Developing the Messoyakha field for commercial export also diversifies Russia's export supply base, as there have been concerns regarding Russia's reliance on declining supergiant fields, improving the ability of the system to withstand shocks affecting single fields (Söderbergh et al., 2010).

I suggest three alternative futures to consider for the Messoyakha gas hydrate field. The first two alternatives consider further resource exploitation at the field, and the third continues the current usage strategy. The proposed alternatives are:

1) Gas hydrate-derived gas is used as part of ongoing natural gas supply to Europe.

2) Development of the Messoyakha field is used as the basis for a new natural gas project supplying China.

3) Gas hydrate is not commercially developed intensively at the Messoyakha field.

The Messoyakha field is already integrated into local and national gas infrastructure via pipelines to major fields south and west (SRI Earth and City, 2018). These fields are connected to the national Unified Gas Supply System by new pipelines (Figure 5.11), brought online in 2017 (Gazprom, 2019a), so export to Europe by the existing network would not require renovation or capacity increase beyond the field. Historically, Russia has been the main natural gas exporter to Europe, and there are contracts for supplying Russian natural gas to European markets until 2035, so gas hydrate-derived gas could provide part of this supply (Mitrova, 2014). Russia exports large quantities of gas to Europe, but is only using 57% of its export capacity, as Russia has invested heavily in pipeline infrastructure, and now has the capability to export more gas than it produces, or Europe demands (Vatansever, 2017). As a result, gas hydrate-derived gas can be exported to Europe without any new infrastructure development.

Alternately the Messoyakha field could be used for supplying gas to China in a new development. Currently, Russia only exports gas to China by pipeline from Sakhalin in the Russian Far East (Gazprom, 2019a), and this export route is too distant to be used for exporting gas from Messoyakha. Therefore, export from Messoyakha to China requires the construction of the proposed Altai pipeline (alternative 2; Figure 5.11). The Altai route is 2700 km, renovating existing pipeline in central Siberia to increase gas capacity, crossing the small western border between China and Russia, and running south from there to the main Chinese gas network near Urumqi (Henderson and Mitrova, 2015).

Finally, Russia has sufficient proven reserves of natural gas to support domestic and export demand at current levels for over 50 years. This figure does not include undeveloped gas resources, which could allow Russian natural gas to last for hundreds of years, if proven viable (Paltsev, 2014). Indeed, Russian gas production capacity currently exceeds demand (Henderson, 2014). With conventional gas here and at other fields, diversification into gas hydrates may be unnecessary, and it may be more beneficial overall to produce this field at low levels for a longer period. Hence, further industrial development of the Messoyakha field may be unjustified (alternative 3).

5.3.3 Criteria

For this study I use the economic criteria market size, in volume (F3) and taxation revenue (F5); the social criteria cultural assets (S1) and subsistence (S6), the environmental criterion habitat impact (E3); and the infrastructure criteria legislation (I1) and lifespan (I2). I provide more detail on the impacts of each alternative in the following sections, with an impact matrix summary presented in Table 5.7. Although the Messoyakha field is not wholly contained within the YNAO (Figure 5.11), I focus my impact analysis on the YNAO as pipeline infrastructure connects to this side of the field. Other criteria from the set in Section 4.3.4 are omitted primarily due to limited, poor quality data, and also to maintain a balanced evaluation that does not focus too heavily on the positive or negative aspects of industrial development. Unlike previous case studies, I do not use resource criteria here, as estimated gas production values directly control taxation revenue and field lifespan. In this small scale study, with fewer criteria, including resource criteria as well would double count the same difference in performance between alternatives.

Where possible I quantify impact (Table 5.7), using qualitative measures where reliable quantification is impossible. Subsistence, cultural impact and habitat impact are measured on an eight point ordinal qualitative scale (none, very low, low, rather low, moderate, rather high, high, very high), following best practice in establishing a simple scale that covers the full range of possible impacts (Cook et al., 1996). I use a seven-value, Likert-style scale to qualify legislation impact (very negative, negative, rather negative, neutral, rather positive, positive, very positive), the maximum number of categories recommended for this scale type to reliably measure impact (Allen and Seamen, 2007).

Table 5.7 *Impact matrix for the proposed alternatives for Messoyakha gas hydrate development. For qualitative criteria, error margins indicate the number of categories difference, for example one category would be the difference from low to very low, or moderate to rather high etc.*

		Alt 1. Europe export	Alt 2. China export	Alt 3. No hydrate development	Error margin
Economic	Market (Tcf/yr)	5.6	2.3	0.1	2
	Taxation (million rubles)	5500	3300	10	2800
Cultural	Subsistence	Moderate	Moderate	None	1 category
	Cultural Impact	None	Very High	None	1 category

Environmental	Habitat Impact	Very low	Very High	None	1 category
Infrastructure	Legislation	Negative	Positive	Rather Positive	0 categories
	Lifespan (years)	12	15	68	9

5.3.3.1 Market

My market estimates quantify the size of market accessible to Messoyakha gas in each alternative, estimated at 2030 to allow sufficient time for production to commence. In addition to the new regions accessed in each alternative, I assume Messoyakha remains able to access the fraction of the Russian market it is currently connected to, heavy industry in Norilsk, for a market of 0.1 Tcf/yr (Norilsk Nickel, 2018).

Despite existing long-term contracts, European countries have been looking to diversify their gas imports away from Russian gas, after disruptions to supply caused by conflict between Russia and the Ukraine (Aune et al., 2017). Additionally, strict carbon policies in Europe could impact gas demand, by lowering overall energy consumption or increasing the market share of renewables (Paltsev, 2014). As a result, European gas demand is predicted to remain constant or slightly decline through 2040, although imported gas will provide a greater fraction of total use, as domestic production declines (Holz et al., 2015). In Russia, western gas fields are declining in production, being replaced by fields further to the east, such as Messoyakha (Figure 5.11). Increased distance increases transport costs, making Russian gas imports less competitive in the European market (Mitrova, 2014). For alternative 1, I follow the prediction that European gas demand will remain consistent, and that Russia will continue to supply much of this due to its existing pipeline infrastructure and long-term contracts (Holz et al., 2015). I use market projections with calculated error margins to estimate Russian gas export to Europe by 2030 as 5.5±1.5 Tcf/yr (Paltsev, 2014).

China is predicted to be the fastest growing gas market in the world, with demand growing 4.4% annually, primarily driven by a policy switch to natural gas to combat pollution issues caused by a heavy reliance on coal for primary power generation (Orlov, 2016a); natural gas generates lower CO_2 per unit energy than other fossil fuels, and produces fewer particulate emissions (Chong et al., 2016). Chinese producers have increased gas production, focussed on developing conventional gas, with relatively slow development of unconventional resources, such as the extensive domestic shale formations (Skalamera, 2018). Despite increasing domestic production, Chinese demand is predicted to outpace supply, leading to an increased reliance on imported gas, including pipeline imports from Russia's Far East (Holz et al., 2015). Russia has entered the Chinese market, but current contracts have relatively low return on investment, in order for Russian gas to remain competitively priced on the Chinese market (Henderson, 2014). Russia has strategic interest in a second export route to China that is linked to the Unified Gas Supply System, where gas could be supplied from many more fields. The most likely route would be across the short border region between Russia and China in the south of the Russian Altai Republic region (Figure 5.11), a route proposed in previous talks between Russia and China (Henderson, 2014). Predicted Russian gas to China by 2030 is 2.2±2 Tcf/yr (Paltsev, 2014).

These demand estimates allow us to create feasible production predictions, by estimating new production motivated by each demand that is reasonable for the size of field. The European export case has the highest demand, so I envision a 500% increase in the number of operational wells, leading to 20 new hydrate wells. Projected demand for Chinese export is less than half of European demand, but the field is strategically placed directly north of the border and Chinese demand is increasing, whereas European demand has stagnated. Therefore, I estimate 12 new wells to produce hydrate-derived gas for alternative 2. In alternative 3, I predict active wells will continue to produce at current rates for the foreseeable future. These production estimates are necessary for estimating impacts by other criteria.

5.3.3.2 Taxation

One primary governmental motivation for developing natural gas is the financial return from taxing production and export. The Russian government controls taxation on oil and gas, to allow its exports to remain competitive, despite the high upstream development and transportation costs for remote fields in harsh environments (Yermakov and Kirova, 2017). Since there is no gas hydrate-specific taxation scheme, I assume the conventional taxation formula will be used, although gas hydrate development may be incentivised differently.

Russian gas production tax varies between fields based upon market price, resource location, formation conditions and the intended market (Yermakov and Kirova, 2017). To estimate tax revenue I use Equation 6, the formula for calculating gas tax used by the Russian government (Tax Code of the Russian Federation, 2000).

$$35 \times V_{gr} \times K_c + T_g \qquad \textbf{Equation 6}$$

The base tax rate is 35 rubles per 1000 cubic metres of gas, which is then adjusted by the base value of a unit of reference fuel (V_{gr}) and by a coefficient which lowers the tax rate for deposits that are considered more difficult to produce (K_c). The final coefficient, T_g, evaluates the cost of transporting natural gas, and was introduced to allow the government to levy higher taxes on

Gazprom specifically, as Gazprom has a monopoly on gas exports and transport (Morozova and Patterson, 2018; Yermakov and Kirova, 2017). Gazprom owns the Messoyakha field and would be responsible for its development (Gazprom, 2019a), but the government does not presently use this control measure (T_g =0) (Yermakov and Kirova, 2017).

The base value of a unit of reference fuel (V_{gr}) is calculated using Equation 7 (Tax Code of the Russian Federation, 2000).

$$V_{gr} = \frac{0.15 \times R_e \times (C_g \times D_g + C_K \times (1 - D_g))}{(1 - D_g) \times 42 + D_g \times 35} \qquad \textbf{Equation 7}$$

D_g is the proportion of gas (as opposed to gas condensates) in gas produced from the field. As I only consider gas production from hydrates, D_g =1, and so the price of gas condensate (C_K) is also not considered. R_e evaluates export return from natural gas, set at R_e = 1 from January 1, 2022 (Tax Code of the Russian Federation, 2000), before the feasible completion time of any proposed alternative. The remaining coefficient is the price of gas (C_g), evaluated by Equation 8 (Tax Code of the Russian Federation, 2000).

$$C_g = C_D \times P_B + C_G \times (1 - P_B) \qquad \textbf{Equation 8}$$

C_D is the state-reported average domestic gas price, which I estimate based upon the reported price in the past five years (Gazprom, 2019b). P_B represents the share of total production by the company producing the field that is used domestically, which is 0.64 for a Gazprom operation (Tax Code of the Russian Federation, 2000). C_G is an average price for gas on global markets, which includes the sale price of gas on foreign markets, transport costs and export duty. I estimate this coefficient using Gazprom data from the past five years, as this data is likely to inform any government estimate (Gazprom, 2019b). These price estimates have some variation, which I use to calculate the overall error margin on taxation in the largest production case (alternative 1).

The final value for K_c used in Equation 6 is the minimum of K_{c1-5}, where K_{c1-5} are five coefficients of factors that may complicate production: field depletion (K_{c1}), geographic location (K_{c2}), end gas use (K_{c3}), resource depth (K_{c4}), and other specific geological factors (K_{c5}). Based upon the production history and resource in place estimates, I calculate the degree of field depletion at 0.36, from the fraction of initial gas in place estimates that has been produced (0.46 Tcf produced compared to 1.27 Tcf initial total resource (Makogon and Omelchenko, 2013)). This value is below the threshold of 0.7 that must be exceeded for the tax rate to be reduced (K_{c1} = 1). Geographically, new projects in the YNAO experience a tax reduction due to its remoteness (Tax Code of the Russian Federation, 2000). However, since this project is an addition to an existing mature field, instead of a new development, this reduction factor does not apply (K_{c2} = 1). The end use of the gas is foreign export for alternatives 1 & 2 (K_{c3} = 1), whereas gas produced for domestic use is taxed at a lower rate (K_{c3} = 0.1), which I use to calculate tax revenue for alternative 3. The gas hydrate deposit is shallower than the 1700 m depth threshold that must be exceeded for tax to be reduced (K_{c4} = 1). The Messoyakha field also does not fulfil any specific condition to qualify for a reduction under K_{c5} (K_{c5} = 1). As a result, none of the reducing factors influence my taxation estimate for alternatives 1 & 2 (K_c = 1), but a reduction is applied for alternative 3 (K_c = 0.1).

In addition to production taxes, alternatives 1 & 2 will also be taxed at the export tax rate for natural gas of 30% (Tax Code of the Russian Federation, 2000). The gas price on a unified European market and the Chinese domestic market are similar enough that I assume them to be identical at 640 roubles/Mcf when calculating the value of exported gas to be taxed (Henderson, 2014; Henderson and Mitrova, 2015).

5.3.3.3 Subsistence

Subsistence in this context includes hunting, fishing, herding, plant collection and other similar activities, as understood by the indigenous communities themselves (Thornton, 2001). Many indigenous Nenets peoples in the eastern YNAO live nomadic lifestyles, herding reindeer for subsistence (Forbes et al., 2009). This subsistence herding has survived prior industrial projects, although cumulative industrial impacts will eventually damage the region beyond where subsistence can be supported (Dwyer and Istomin, 2008). Industrial development fragments pastures with infrastructure that can also block migration routes, and reduces the ability of pasture to regenerate on established migration routes (Forbes et al., 2009). Losing migration routes can prevent access to pastures, and remaining routes can become bottlenecks, overused by many migrating herds (Degteva and Nellemann, 2013). The lack of environmental regulation has helped the Nenets continue their lifestyle unhindered (Forbes, 2013), but now affords them little protection from industrial impacts. I estimate up to 60% of the unindustrialised Messoyakha field land is high quality pasture, and 30% is moderate quality pasture, with the remaining 10% not pasture quality (Kompaniec et al., 2015). These pastures have a patchy distribution, making high quality pasture difficult to avoid when drilling wells, and the more wells that are developed, the greater the likelihood of damaging or isolating pastures. The Nenets do not rigidly control reindeer movement during herding, with reindeer herds occupying roughly rectangular regions around 60 km^2 in size, so industrial development will constrict these regions (Dwyer and Istomin, 2008). Alternative 1 causes more subsistence impact in the field than alternative 2 due to the higher number of wells drilled.

Although alternative 2 has less impact on subsistence herding at the field, it also includes additional infrastructure development in the Altai that has potential to disrupt subsistence activity. Livelihoods in the Altai region are more varied than in the Yamal, with farming, mineral extraction and the timber industry providing income, so the indigenous Altai population is less reliant on subsistence resources than the Nenets (Badenkov et al., 2012). However, the animal populations used for subsistence in the Altai are already declining due to pressure from tourism (Remmers, 2017), and a pipeline would provide another access route for these activities. Illegal hunting is also common in the Altai, with traditional hunting grounds overlapping with nature reserves, and illegal trophy hunting by visiting tourists (Remmers, 2017). Indigenous Altai hunting is only socially regulated, as regulations on hunting and environmental protection are generally opposed, meaning these resources are not protected in the event of large industrial development, especially if this development is supported by the government (Halemba and Donahoe, 2008). Therefore, there would be a subsistence impact from pipeline development in the Altai region, although probably less severe than the impact in the YNAO. When evaluating impact qualitatively, I consider the joint impact from the field and pipeline in alternative 2 equivalent to the more intensive impact at the field in alternative 1, especially as subsistence is more integral to the Nenets than the Altai, but in both cases subsistence generally occurs over a wider area than that affected by gas hydrate development. As I have used a qualitative mechanism, the error in my impact assessments from uncertainty in the available data is contained within one impact class.

5.3.3.4 Cultural Assets

In addition to subsistence resources, there are also specific sites with cultural or spiritual significance to the indigenous peoples of the region that may be impacted. Therefore, I evaluate the impact on spiritual resources separately to subsistence, which focuses on resources integral for base survival. The official record of such sites, the Unified State Register of Cultural Heritage Objects (Historical and Cultural Monuments) of the Peoples of the Russian Federation, lists 46 cultural assets in the YNAO (Ministry of Culture of Russia, 2019), none of which would be affected by development of the Messoyakha field. By contrast, the Unified State Register has 4480 recorded assets in the Altai Republic (Ministry of Culture of Russia, 2019), many coinciding with the pipeline route, as the proposed pipeline follows the river corridor that has been inhabited for 5000 years (Plets et al., 2011). This register is not a complete record, especially for sacred sites, and inclusion on the register does not necessarily afford a site protection in reality (Vinokurova and Dambaeva, 2008). There has been limited independent study, but Plets et al. (2011) showed that over 300 monuments and archaeological sites would be impacted by development of 5.5% of the Altai pipeline route, suggesting thousands of cultural sites could be impacted by the full Altai pipeline.

In addition to impacts on specific sites, the Altai mountains overall have great religious significance for the Altai people, reflected by their UNESCO World Heritage status (Bourgeois et al., 2007). Since Altai culture centres on a spiritual connection to the land, any industrial damage removes this sacred value, so a high cultural impact is unavoidable with developing the Altai route (Plets et al., 2011). When estimating cultural impact, I use a qualitative ordinal categorical description based upon the number of sites impacted, rather than a numerical estimate of number of sites, as any quantitative figure will be imprecise as much of the region has not been archaeologically surveyed.

Overall, the impact on cultural sites from producing the Messoyakha field is very low to none as there are few to no assets likely to be affected, but developing pipeline infrastructure in the Altai could be devastating to cultural assets. Altai industrial development is likely to be opposed internationally, further protecting the area. In my estimation of impact, the error margin considers that efforts may be made to preserve the sites, although considering the number of sites, the high time and cost needed to accurately survey them all, and the lack of legislation mandating this conservation effort, it is unlikely that more than a cursory effort would be made (Plets et al., 2011).

5.3.3.5 Habitat Impact

I consider damage to the natural environment irrespective of derived human utility by considering habitat impact. As well as direct habitat loss, there are a number of ways that industrial development could degrade habitat quality over time. As part of developing the Messoyakha field, there would be a number of new infrastructure routes built, that would increase general accessibility, increasing illegal hunting near gas fields and polluting land in the surrounding area, causing a decline in scrub vegetation (Forbes et al., 2009). Environmental regulation of industrial development is limited, so land is often too polluted to regain its full ecosystem value unassisted, and restoration is not mandated after activities cease (Forbes et al., 2009). Methane leakages from pipelines could damage the local and global environment, as 0.6%-2% of produced gas is estimated to be lost during transmission (Lechtenböhmer et al., 2007; Söderbergh et al., 2010). Methane absorbs heat in the atmosphere more effectively than CO_2, so leakages may have a cumulative climatic effect that impacts many species and habitats (Lechtenböhmer et al., 2007). As the length and route taken by gas for export to Europe is impossible to predict, I cannot consider this impact within my case study.

I evaluate habitat impact by determining the species present, and their risk from the threats of industrial development. I use data from the IUCN Red List as in my previous case studies (IUCN, 2019) to evaluate which plant and animal species are present in the region and their conservation status, assigning a greater impact where impacted species have greater extinction risk. The IUCN red list has seven classification categories for species evaluated, each representing a different level of extinction risk. The categories are, in increasing risk; least concern, near threatened, vulnerable, endangered, critically endangered, extinct in the wild and extinct (IUCN, 2019). Although the most comprehensive data available, the red list still has shortcomings as only a small proportion of known species are assessed, and the information is not always current (Bennun et al., 2018), but it is the most suitable data for my assessment due to its consistent style over a broad area.

For alternative 1, I only consider species whose habitats overlap with the field in my evaluation, as the remaining export infrastructure already exists. Overall, 170 species are potentially impacted, 6 of which are designated as near threatened and 7 are designated as vulnerable (IUCN, 2019). For alternative 2, species inhabiting the Altai pipeline route would be affected, in addition to all species considered in alternative 1. The Altai has exceptionally high plant diversity, and has been designated by the World Wide Fund for Nature (WWF) as a priority ecoregion, a designation reserved for the world's most unique and irreplaceable natural environments (Badenkov et al., 2012). The alternative 2 pipeline route could impact 466 species, in addition to those impacted in the field area, 20 of which are near threatened, 17 vulnerable, 4 endangered and 1 critically endangered (IUCN, 2019). I convert these species numbers, weighted for extinction risk, to qualitative impact estimates to accommodate large uncertainty in which species are present from using large-scale data. In establishing impact, I consider that the Messoyakha field has historically been an active oil or gas field, so species present have experienced industrial development, whereas the Altai plateau is relatively unindustrialised, and species here may have a more adverse response as a result. If this assumption is incorrect, it could introduce an error of one category into my impact estimates, so I use this value for the error margin on all alternatives.

5.3.3.6 Legislation

By evaluating legislation, I consider if the strategic goals of the Russian government and its export trade partners would aid or hinder gas hydrate development. Unlike other criteria used, legislation acts as a driver of development, rather than an impact. In this way legislation may influence initial alternative design, but in many cases hydrate-specific legislation is absent and may only result once gas hydrate development is seriously considered. In either case, legislation will influence which alternative is chosen. A qualitative measure of legislation impact is produced by evaluating volume of legislation, and relative weight of beneficial legislation to legislation hindering industrial development.

Russia has previously limited domestic gas prices to help market transitions after the end of the Soviet Union (Orlov, 2016b). Supressed domestic prices make the relatively high costs of gas hydrate prohibitive, but the government has gradually removed this practice in recent years, and all price restrictions will likely be lifted by the time Messoyakha commercialisation begins (Orlov, 2016b). New and diverse field developments are incentivised to maintain growth in the oil and gas sector, as gas provides 7% of the Russian federal budget (Yermakov and Kirova, 2017). Development at Messoyakha could be considered part of this planned diversification, as the field has not been a major gas supplier since the 1970s, and new development would be focussed on unconventional resources, suggesting the government would view this development favourably.

One stated goal of the Russian government is “economic utilization of unconventional natural gas reserves” (Institute of Energy Strategy, 2010), which suggests there would be support for gas hydrate development, but there is no specific legislation promoting unconventional gas development (Ocelík and Osička, 2014). With abundant conventional gas in Russia, unconventional resources have not been prioritised, as the government focuses on returns from its current system, with no need to diversify. As a result, gas hydrate development is not promoted or restricted when compared with conventional development.

As alternative 1 has Russian gas exported to European countries, I consider EU legislation for this alternative. While some non-EU member states in Europe use Russian gas, 70% of total Russian gas exports are to the EU (Casier, 2011), so the EU can be considered the primary market dictator. EU-level legislation controls the suitability of EU states as trade partners, and is simpler to evaluate than considering each national government individually. The EU has set strict carbon limits of a 40% reduction in greenhouse gas (GHG) emissions from 1990 levels by 2030, and an 80-95% reduction by 2050 (Fragkos et al., 2017). Natural gas use would increase as a result, as it displaces other fossil fuels with higher emissions, such as coal. However, a secondary target is to increase the market share of renewables to 27% by 2030 (Fragkos et al., 2017), reducing the market share available for natural gas. These two targets effectively cancel each other out, so EU natural gas usage is expected to remain constant through 2050 (Fragkos et al., 2017).

Although gas demand is expected to continue at current levels, the EU is seeking to reduce its dependency on Russia for gas. The EU imposed sanctions on Russia over its destabilising role in the Crimea region (European Union, 2016), but Europe is too dependent on Russian gas to suspend trade entirely (Zaynutdinov, 2015). In addition to concerns surrounding Russia as a trade partner, Gazprom specifically has been regulated against, to promote competition on European markets. Gazprom has significant power for a single company, with a legal monopoly to export natural gas from Russia by pipeline (Morozova and Patterson, 2018), and 25-100% ownership shares in gas distribution companies in ten European nations (Bilgin, 2011). The EU Third Energy Package was implemented to prevent companies owning both natural gas infrastructure and the gas flowing through it, which limited new Gazprom developments in Europe, including cancelling the planned South Stream project transporting Russian gas through the Black Sea (Skalamera, 2018). The European Commission has also found Gazprom in breach of European anti-trust laws, as Gazprom priced gas higher in countries where it had a controlling share of the market (Siddi, 2017), resulting in restrictions on Gazprom, forcing new gas prices to be in line with the entire European market (European Commission, 2018). Hence, despite the large market size, Gazprom is unable or unwilling to invest further in the European market. Overall, gas trade between Europe and Russia is a reluctant partnership, especially on the part of the EU, so legislative distrust would hinder alternative 1.

Alternative 2 is impacted by legislation controlling natural gas use in Russia and China, and trade between the two countries. The 13th Five-year Plan, used to guide Chinese policy, aims to promote connection of energy infrastructure with other natural gas producing countries in the Belt and Road Initiative, a global strategic plan for infrastructure development (National Development and Reform Commission P.R.C., 2016), which includes Russia. The Plan promotes natural gas use domestically to reduce GHG emissions, as air quality is a major issue for China (Dong et al., 2017). It proposes natural gas providing 10% of total energy consumption by 2020, and expansion of the existing natural gas pipeline infrastructure by 40000 km, with a specific focus on increasing the longitudinal connectivity of the network (National Development and Reform Commission P.R.C., 2016). Investments in national and international gas infrastructure both support development of the Altai pipeline, as the Altai region of China is west of most demand centres, in a region that is currently poorly connected. The Chinese government controls natural gas sale prices on its domestic market (Dong et al., 2015), so it may be difficult to achieve profitability with the high transportation costs of the Altai route, if the Chinese government is unwilling to price the gas accordingly. However, the government is looking to reform its natural gas pricing mechanism, to create a system that reflects market dynamics, which may make the market more inclusive to foreign imports (National Development and Reform Commission P.R.C., 2016). Russian energy strategy towards the Sinosphere has progressed from a vague 2010 aim to utilise Asia-Pacific markets, to more recent aims to rapidly enter the Asian market and complete negotiations with China (Shadrina, 2014). Where Russia and China's interests diverge is the location of any infrastructure link, as China prefers infrastructure links in the Russian Far East, close to Chinese population centres. Accordingly, Russia developed the Power of Siberia pipeline (Figure 5.11), but a second connection is still possible. Conversely, Russia is keen to link its Unified Gas Supply System to China in western Siberia (Figure 5.11), as gas could then be directed to China instead of Europe, giving Russia more negotiating power with the EU (Henderson and Mitrova, 2015). In 2014 Gazprom signed a memorandum of understanding with China regarding the Altai pipeline, with gas export anticipated to begin in the mid-2020s (Yafimava, 2015). A memorandum of understanding has no legally binding commitment, and discussions have not progressed further; the Altai pipeline is not currently listed as a commercial project by Gazprom (Gazprom, 2019a). This situation is not without precedent, a decade elapsed between the memorandum of understanding for the eastern Power of Siberia pipeline and a formal agreement outlining export terms (Henderson, 2014), a timeline that would align with Messoyakha gas hydrate development, which is unlikely to commence before 2030. Considering China is continuing the Belt and Road initiative, and both sides have shown interest in this specific export route, legislation from both countries generally supports alternative 2.

The gas industry remains an important part of the Russian economy, and the Russian government may favour the long term stability (Paltsev, 2014), but lower short term revenue, provided by alternative 3. Norilsk exists due to nearby nickel deposits, and the state government is involved with the company mining these deposits, Norilsk Nickel (Humphreys, 2011), and may want to ensure these factories are continually supplied with gas to protect their investments and strategic resources. Natural gas provides the majority of Russian energy (Orlov, 2015), and the government prioritises domestic supply for long term security, so desires a large domestic reserve. Russia has struggled to keep its gas imports competitive as its import partners develop cheaper domestic alternatives, such as shale gas (Paltsev, 2014). High transport costs being passed on to consumers, or reducing profit margins for producers, have also been one of the main factors prohibiting Russia from entering the Chinese market (Shadrina, 2014). As a result of its current pricing issues, the Russian government may prefer not to develop gas hydrate at present, with its higher production costs than conventional gas.

5.3.3.7 Lifespan

Gas will be needed at the Norilsk industrial hub for the foreseeable future (Kalotay and Sulstarova, 2010), and this gas would have to come from another field should Messoyakha be exhausted, necessitating new infrastructure. Due to current oversupply in the wider Russian gas market, and long-term local demand, there is a potential opportunity cost associated with not preserving this resource for future use. The benefit derived from present-day use of this gas supply may be less than the potential benefit of using this gas in future, when Russia has less natural gas overall, and this gas supply has continued benefit through its role in powering Norilsk mining. As the Messoyakha field is potentially being recharged by gas hydrate-derived gas during production (Grover et al., 2008), directly targeting the hydrate removes this replenishment mechanism. The more intensively gas hydrate is targeted, the faster the field loses pressure support and production is exhausted. Therefore, I include field lifespan as a criterion, with a longer lifespan preferred.

I use projected gas production rates based upon the history of the field to predict lifespan of the estimated Messoyakha resource under each scenario (Makogon and Omelchenko, 2013). After depletion of the hydrate resource, the newly drilled wells would continue to produce conventional gas, resulting in preliminary lifespan estimates of 35 years for alternative 1, 52 years for alternative 2 and 223 years for alternative 3 (Appendix D). These are significant overestimates; the entire resource cannot feasibly be produced, especially as gas hydrate is currently maintaining reservoir pressure, and once solid hydrate is depleted additional pressure support would be required. If pressure support was not economically viable, as it may not be for a relatively small field such as Messoyakha where there are other regional targets, production would decline rapidly after solid gas hydrate is depleted. For my final lifespan estimates (Table 5.7) I apply a decay function from the moment solid gas hydrate ceases to exist (Appendix D), following the evolution of a declining conventional gas field (Söderbergh et al., 2010), as decline projections have not been established for gas hydrate fields. For alternative 1, hydrate depletion occurs after 9 years of production, for alternative 2 after 13 years of production due to the lower number of wells, and if hydrate is not directly targeted, but continues to maintain reservoir pressure (alternative 3), hydrate is depleted after 66 years. These are again optimistic values, especially for the no development case, as they assume all solid hydrate can be converted to gas, and the resulting gas flows unimpeded to the well, irrespective of the petrophysical properties of the intermediate reservoir. Production is terminated a few years after gas hydrate exhaustion in each case, as production ends with free gas produced alone, resulting in ultimate lifespan estimates of 12 years, 15 years and 68 years. I terminate production when it reaches a fraction of present day values, where the Messoyakha field would no longer be cost effective to keep online (Appendix D). The error margin on these values originates due to uncertainty surrounding the role of gas hydrate in production, the future pressure conditions of the well, and when production would be terminated.

5.3.4 Stakeholders

I have considered potential stakeholders in a future field study at Messoyakha to ensure my six stakeholder groups (government, industry, indigenous community, local community, environmental NGOs, scientific community) are comprehensive in this setting that is geographically and socially distinct to the two previous North American examples. No further stakeholder groups are known beyond those listed. Inclusion of environmental NGOs and indigenous stakeholders would be especially important for this site, as these groups often have their views ignored or supressed when industrial development projects are discussed (Yakovleva, 2011).

Government: There are structural similarities between the government stakeholders at Messoyakha and in Alaska, with national and regional government having different priorities and accountability in both locations. Nationally, gas hydrate development will be regulated by departments including the Ministry of Natural Resources and Environmental Protection, the Ministry of Industry and Trade, the Ministry of Energy, the Ministry of Economic Development and the Ministry of Labour and Social Affairs. Regionally, the YNAO legislative assembly is heavily dependent on revenue from the oil and gas industry (Kharitonova and Vizhina, 2011), so government stakeholders could originate from many areas.

Industry: The Messoyakha field would be developed by Gazprom, a company majority owned by the Government of Russia, who would also process, transport, export and sell the gas. Therefore, appropriate industry representation would only require including the range of positions that may exist within Gazprom. Field workers are also included within this group, as over 15% live beyond the YNAO, and those in the YNAO primarily live in cities with rotational work schedules (Nalimov and Rudenko, 2015), so employment is not wholly local.

Indigenous Community: Overall there are 43,000 people who ethically identify as Nenets, around half of whom still live nomadic reindeer herding lifestyles (Istomin and Habeck, 2016). These people form the major indigenous community in the YNAO, and so could provide insight on how industrial development would affect their lifestyle, and whether any jobs or income created would benefit them. The UN considers indigenous peoples worldwide as having a right to self-determination of how their land is used (Gilbert, 2016) so, depending how far this is adhered to, the indigenous community may dictate whether development can proceed. Additional indigenous stakeholders who should be included are the Altai people, a major ethnic group in the area crossed by the alternative 2 pipeline.

Local Community: Beyond the indigenous community, the harsh climate and remoteness of the area limit local population. Applying the same principle used in Alaska, where potential end users or those developing infrastructure are consulted, stakeholders could be found in Norilsk. Overall, the number of stakeholders in this group is limited.

Environmental NGOs: Environmental NGOs in Russia are generally smaller and less organised than their North American counterparts, and as such have less influence (Crotty, 2009). As a result, the main NGOs at work are local branches of multi-national organisations, such as WWF Russia. There is significantly more advocacy in the Altai region than the YNAO, due to higher perceived environmental and cultural significance (Badenkov, 2011), so there are a range of organisations here who may wish to provide input.

Scientific Community: The Messoyakha field is the most studied gas hydrate province in Russia (Makogon, 2010), and has received interest from international scholars, particularly debating the contribution of gas hydrate to conventional production (Collett and Ginsburg, 1998). The field is still under-studied compared to its North American or Asian counterparts, with no dedicated gas hydrate drilling, so many important parameters remain unknown (Makogon and Omelchenko, 2013). Even so, there are a range of gas hydrate scientists likely to have different views on producing the field. The YNAO and Altai regions are also of interest to ethnographers studying indigenous peoples (e.g. Dwyer and Istomin, 2008), who would provide a different viewpoint from within the scientific community.

5.3.5 Weighting

In lieu of direct experimental data from stakeholder interviewing, I used a series of hypothetical weights, with my experience in Alaska as the initial basis. The first weighting scheme gives equal weight to all criteria to create an unbiased position, although the number of sub-criteria is not consistent, so each criterion is not weighted equally (Table 5.8). In Alaska, my impact matrix included resource criteria, and did not include infrastructure criteria, so I cannot directly use weights from that case study here. Instead, I use my experience in Alaska to understand likely maximum weights for criteria of importance. I create two extreme positions (Figure 5.12), giving 70% of weight to economic or infrastructure criteria (Table 5.8), to cover the possible range of weights (Figure 5.12). Rather than creating two separate weighting schemes with high environmental and social weight, I create one scheme (scheme 3) with high weight given to both (Figure 5.12), as my experience in Alaska showed that most stakeholders who gave high weight to the environmental criteria also gave high weight to social criteria. Infrastructure is most likely a strong consideration for government stakeholders, who control legislation, and will have to consider how any projects fit into their long term regional development plans.

5.3.6 Thresholds

This protocol requires three thresholds (Indifference, Preference and Veto) for each of the criteria in Table 5.7, and the values of these thresholds determine the resultant preference between alternatives. These thresholds and resulting preference are explained in Section 5.2.4. To explore potential computational results, preference thresholds are varied from close to the indifference threshold to maximum values sufficient to cover the performance range of all alternatives on each criterion (Table 5.9). Creating every possible combination of preference threshold values, with one threshold for each criterion, results in 6480 combinations for each set of criteria weights. To simulate the resulting decision from each set of preference thresholds, I use the

MCDA-ULaval decision making software (Abi-Zeid et al., 2015) to simulate each decision combination. In these scenarios, indifference thresholds (Table 5.9) are fixed at the calculated error margins for the impact estimates (Table 5.7). Four criteria were measured qualitatively on an eight category scale (none, very low, low, rather low, moderate, rather high, high, very high), so preference thresholds for these criteria are given as a number of categories. Veto thresholds are not included in this first set of scenarios focussing on the impact of varying preference thresholds.

Table 5.8 *Range of weighting schemes used to represent different hypothetical stakeholder priorities*.

		Scheme 1	Scheme 2	Scheme 3	Scheme 4
		Homogenous weights	*Economic focus*	*Environmental/ social focus*	*Infrastructure focus*
Economic	*Market*	1	2.45	0.525	0.35
	Taxation	1	2.45	0.525	0.35
Social	*Subsistence*	1	0.35	2	0.35
	Cultural Impact	1	0.35	2	0.35
Env.	*Habitat Impact*	2	0.7	4	0.7
Inf.	*Legislation*	1	0.35	0.525	2.45
	Lifespan	1	0.35	0.525	2.45
	Percentages				
	Economic	25	**70**	10	10
	Social	25	10	**40**	10
	Environmental	25	10	**40**	10
	Infrastructure	25	10	10	**70**

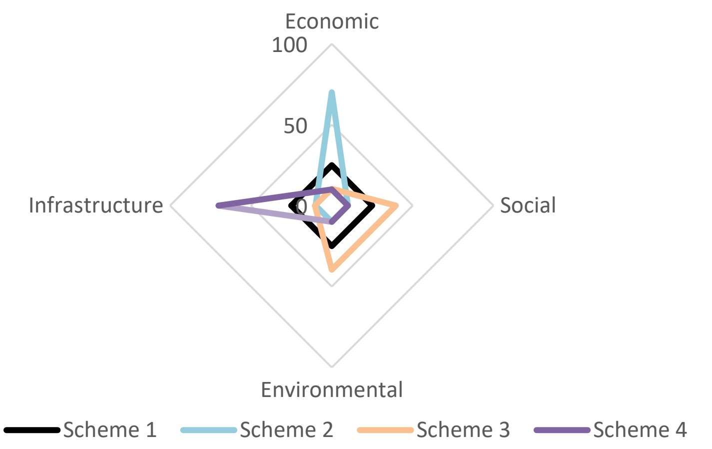


Figure 5.12 *Visualisation of weight schemes in Table 5.8, showing percentage of total weight given to each of the four criteria*.

Using the same approach I run a second series of scenarios to test the impact of veto thresholds. In these scenarios indifference thresholds are again fixed at the data error margins, and preference thresholds are now also fixed at these minimum values. Veto thresholds are then varied over a sufficient range to explore the decision space (Table 5.10). In total there are 2187 combinations of varying veto threshold values for each weighting scheme. I run one scenario for each combination of veto thresholds using the MCDA-ULaval decision making software (Abi-Zeid et al., 2015).

Table 5.9 *Indifference thresholds and range of preference thresholds used in the ELECTRE III simulation for Messoyakha. For qualitative criteria, threshold values indicate the number of categories difference, for example one category would be the difference from low to very low, or moderate to rather high etc.*

		Indifference	Preference
Economic	Market (Tcf/yr)	2	[2, 3, 4, 5, 6]
	Taxation (million rubles)	2800	[3000, 4000, 5000, 6000]
Cultural	Subsistence	1 category	[1, 3, 5] categories
	Cultural Impact	1 category	[2, 4, 6] categories
Environmental	Habitat Impact	1 category	[1, 3, 5, 7] categories
Infrastructure	Legislation	0 categories	[1, 3, 5] categories
	Lifespan (years)	9	[20, 40, 60]

Table 5.10 *Range of thresholds used for variable veto simulations at Messoyakha. For qualitative criteria, threshold values indicate the number of categories difference, for example one category would be the difference from low to very low, or moderate to rather high etc.*

		Indifference & preference	Veto
Economic	Market (Tcf/yr)	2	[2.5, 5, 7.5]
	Taxation (million rubles)	2800	[4000, 5000, 6000]
Cultural	Subsistence	1 category	[3, 4, 5] categories
	Cultural Impact	1 category	[2, 4, 6] categories
Environmental	Habitat Impact	1 category	[3, 5, 7] categories

Infrastructure	Legislation	0 categories	[1, 3, 5] categories
	Lifespan (years)	9	[20, 40, 60]

5.3.7 Results

I analyse these results using the same approach as in the Canadian case study, comparing the distribution of results for each weighting scheme with the range of thresholds, to identify which thresholds have a controlling influence on the final result. Results for scenarios with varying preference thresholds are summarised in Table 5.11, and scenarios with varying veto thresholds are summarised in Table 5.12.

Table 5.11 *Summary of possible results for each weighting scheme in preference scenario simulations, each column representing one set of scenarios with a given weighting scheme. Square brackets indicate alternatives are equally ranked. An orange tick represents that the specified result is possible for a given weighting scheme. Other rankings that did not result from any scenario are not shown. Econ: Economic; Soc/Env: Social/Environmental; Infra: Infrastructure.*

		Preference scenarios			
Weighting Scheme		Uniform	Econ	Soc/Env	Infra.
Possible Alternative Rankings	*[1,3], 2*	✓	×	✓	×
	[2,3], 1	×	×	×	✓
	1, [2,3]	×	✓	×	×
	3, [1,2]	×	×	×	✓
	1, 2, 3	×	✓	×	×
	1, 3, 2	✓	✓	×	×
	3, 1, 2	×	×	✓	×
	3, 2, 1	×	×	×	✓

Under the homogeneous weighting scheme, there are two possible results, both with alternative 2 ranked least preferred overall (Table 5.11). Between the other alternatives, alternative 1 only outranks alternative 3 at low preference thresholds for market and taxation (Figure 5.13a, b), where both other alternatives are strongly preferred to alternative 3 on both criteria. The impact of preference thresholds for legislation is more complicated, as alternative 3 is not outranked at P(legislation) = 3, but is outranked at both higher and low preference thresholds (Figure 5.13f). At higher and lower thresholds, preference relationships between alternatives are either all strong or all weak on this criterion, but at P(legislation) = 3 there are a mixture of strong and weak preferences on this criterion, resulting in overall indifference between alternatives 1 and 3. The remaining criteria do not influence the final result, with both rankings possible for all preference values (Figure 5.13c, d, e, g).

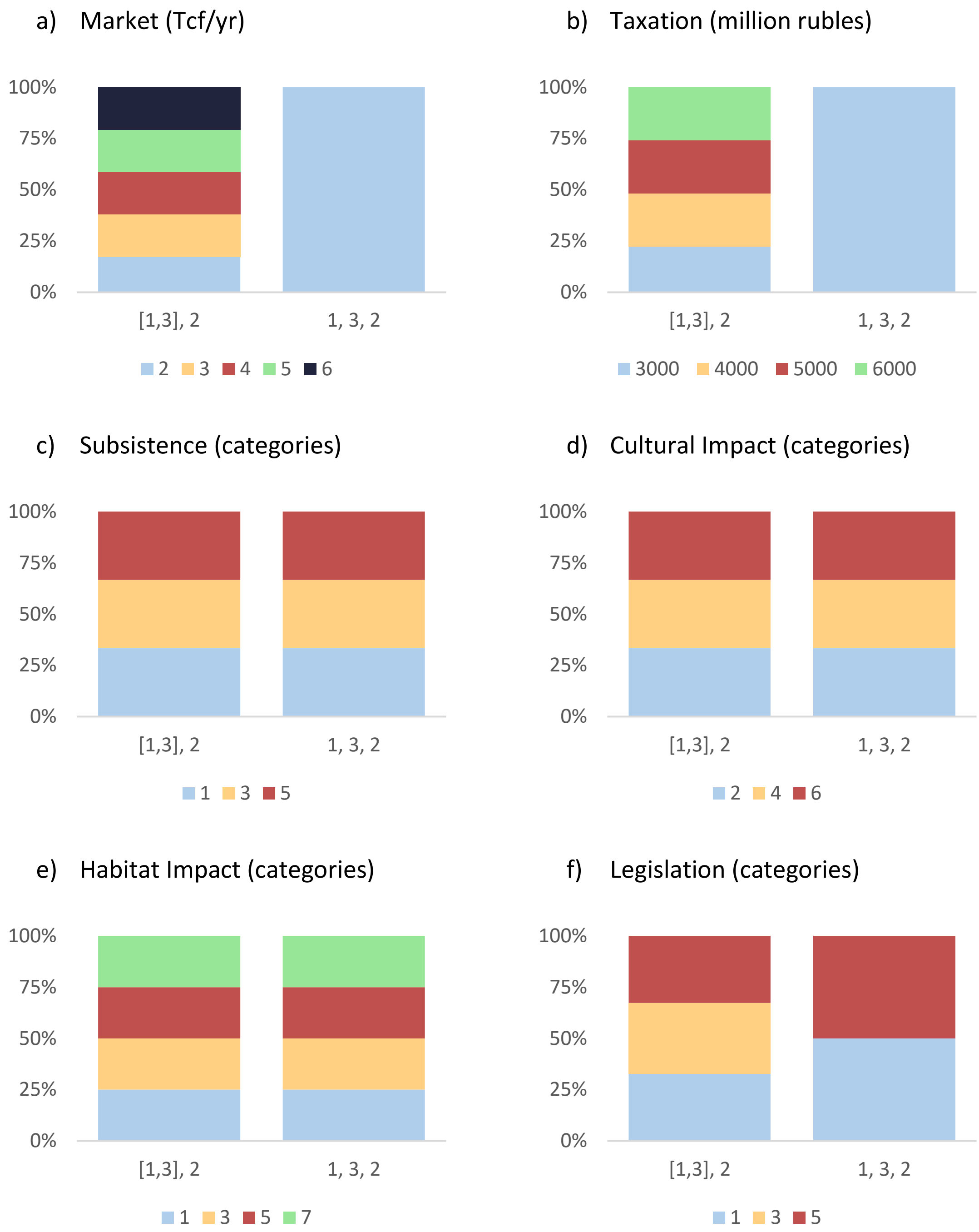
With most weight allocated to the economic criteria, three alternative rankings develop (Table 5.11), all with alternative 1 ranked first, but the order of the remaining alternatives varies (Table 5.11). The two heavily weighted criteria, market and taxation, provide most discrimination between results (Figure 5.14a, b). Low preference thresholds on these criteria cause both alternatives to be strongly preferred to alternative 3, which is outranked overall as a result (Figure 5.14a, b). By contrast, high preference thresholds on these criteria weaken the preference relationship, and the superior performance of alternative 3 elsewhere allows it to outrank alternative 2 overall (Figure 5.14). Alternative 3 only outranks alternative 2 on large threshold values for legislation, as alternative 2 has superior performance on this criterion, so this criterion also controls the end result (Figure 5.14f). Preference values on the remaining low weight criteria do not influence the final result (Figure 5.14d, e)

With high social and environmental weighting, there are two possible results (Table 5.11), again with alternative 2 least preferred in both cases. Alternative 2 has poor performance on all social and environmental criteria measured here (Table 5.7), causing its outranking. The remaining alternatives are differentiated only by the preference thresholds for subsistence (Figure 5.15c), as the only criterion with high weight where the preference between alternatives 1 and 3 changes. At low preference thresholds for subsistence, alternative 3 outranks both other alternatives on this criterion, and so outranks both alternatives overall. As the preference threshold increases, the strength of preference decreases, until alternatives 1 and 3 are ranked equivalent overall at P(subsistence) = 5.

With most weight given to infrastructure criteria, there are three possible results (Table 5.11). Of the high weight criteria, the preference threshold for legislation controls the end result (Figure 5.16f). At P(legislation) = 1, both alternatives are strongly preferred to alternative 1 on this criterion, and it is outranked overall as a result. This ranking also requires a high preference threshold for market, sufficient that alternative 1 is only weakly preferred on this criterion, enabling alternative 1 to be outranked overall. At P(legislation) = 5, both alternatives are weakly preferred to alternative 1, and the superior performance of alternative 3 on the lifespan criterion causes it to outrank both other alternatives overall. Finally, at P(legislation) = 3, alternative 2 is strongly preferred to alternative 1, but alternative 3 is only weakly preferred. Alternative 2 only outranks alternative 1 at high market threshold values, where there is only a weak preference in favour of alternative 1 on this criterion, and this is overhauled by its performance on the remaining criteria. For most criteria in these scenarios, the preference threshold value does not influence the final ranking result (Figure 5.16b, c, d, e, g).

In the veto threshold simulations, compared to the preference threshold scenarios, a greater range of results were possible for most weighting schemes, except for the economic weighting scheme (Table 5.12). Even though preference thresholds were not varied, most of the results from preference only scenarios continued to be possible outcomes when veto thresholds were introduced. Compared to the preference threshold scenarios, with veto thresholds there is much more consistency in results across weighting schemes, as most of the same results are possible under every weighting scheme (Table 5.12). One possible result in all veto threshold scenarios had all alternatives ranked equally, a result that never occurred where only preference thresholds were used. This result occurs because veto thresholds prevent outranking if the performance of an alternative is sufficiently inferior, so a veto acting on any criterion is sufficient to prevent outranking overall.

Veto thresholds on legislation consistently influence the final result (Figure 5.17), whereas veto thresholds on most other criteria do not differentiate between results (Appendix E). This outcome suggests that most veto thresholds only further reinforce an already outranked alternative as not preferred. Veto thresholds favour alternative 3, with low negative environmental or social impact, making it the first or second ranked alternative in all cases (Table 5.12).



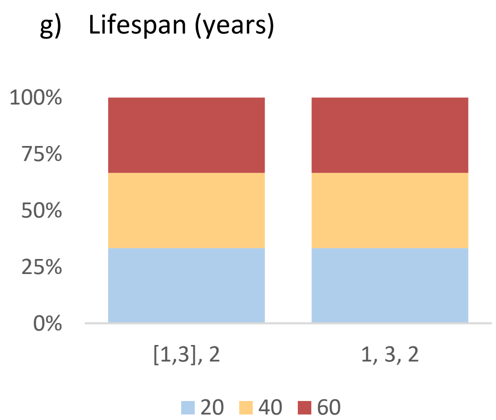


Figure 5.13 *Summary of scenario results with uniform weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios.*

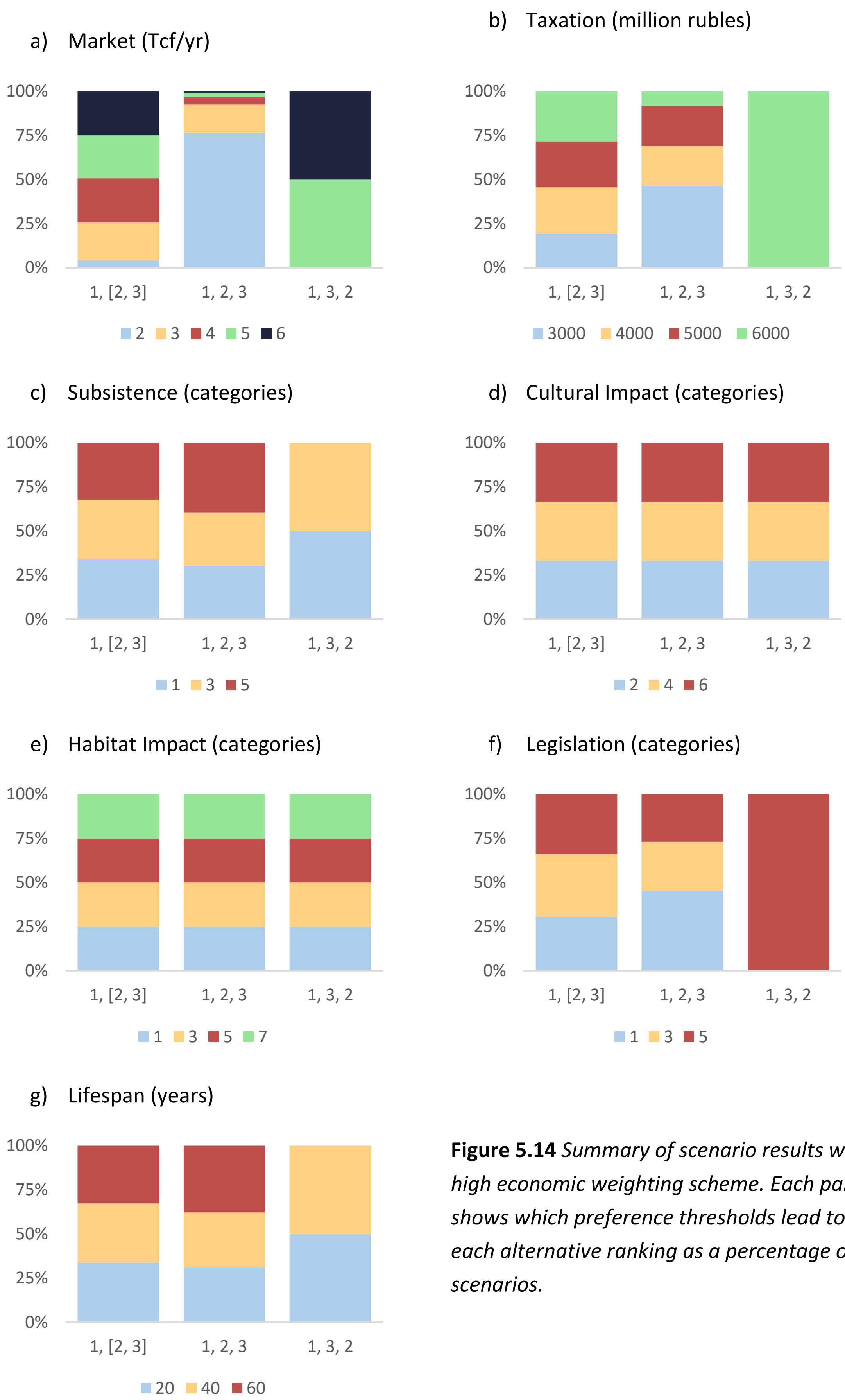
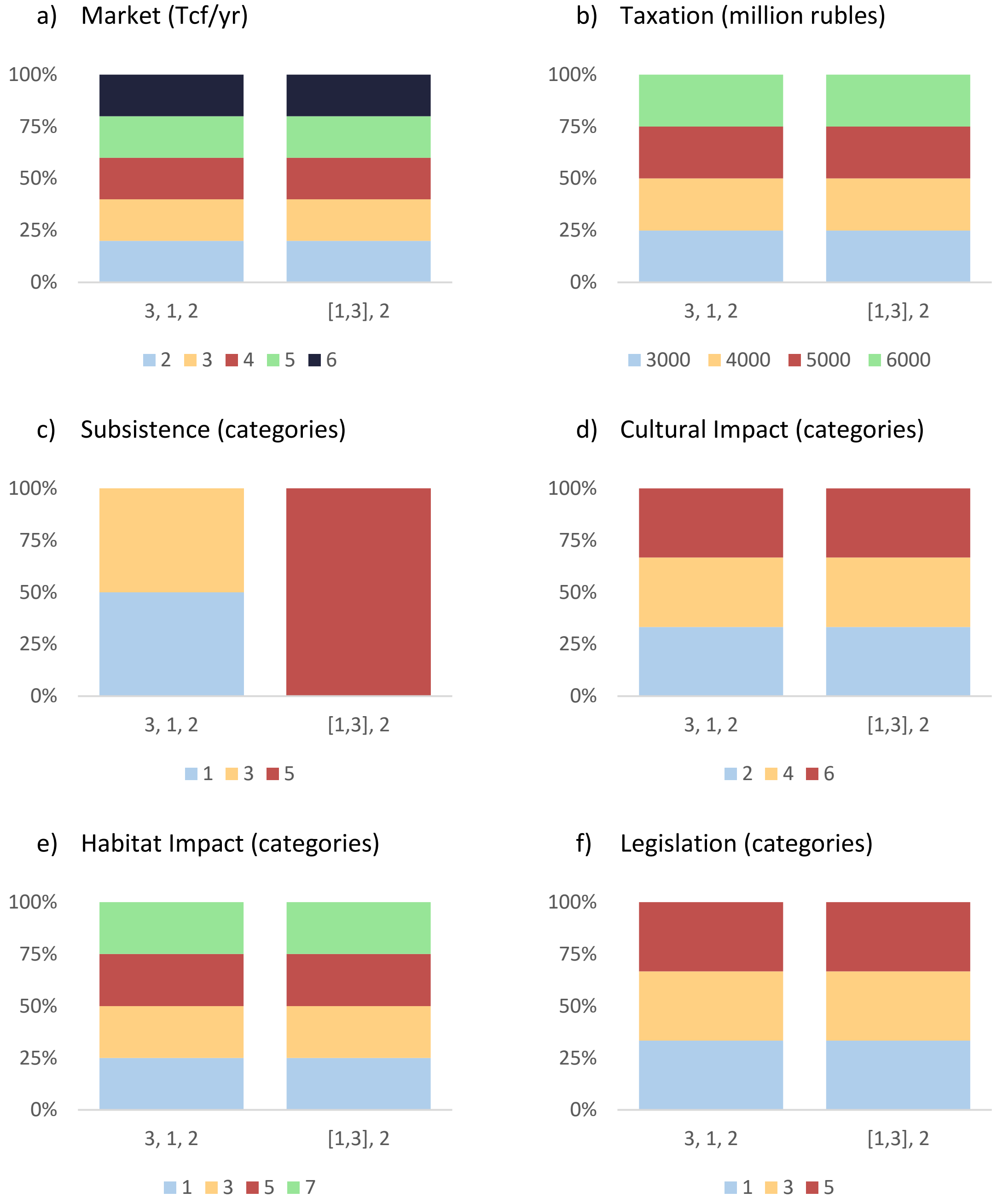


Figure 5.14 *Summary of scenario results with high economic weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios.*



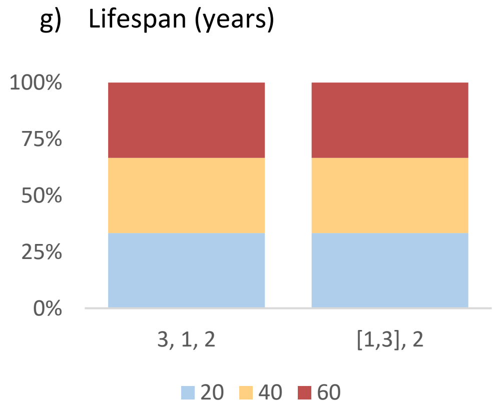
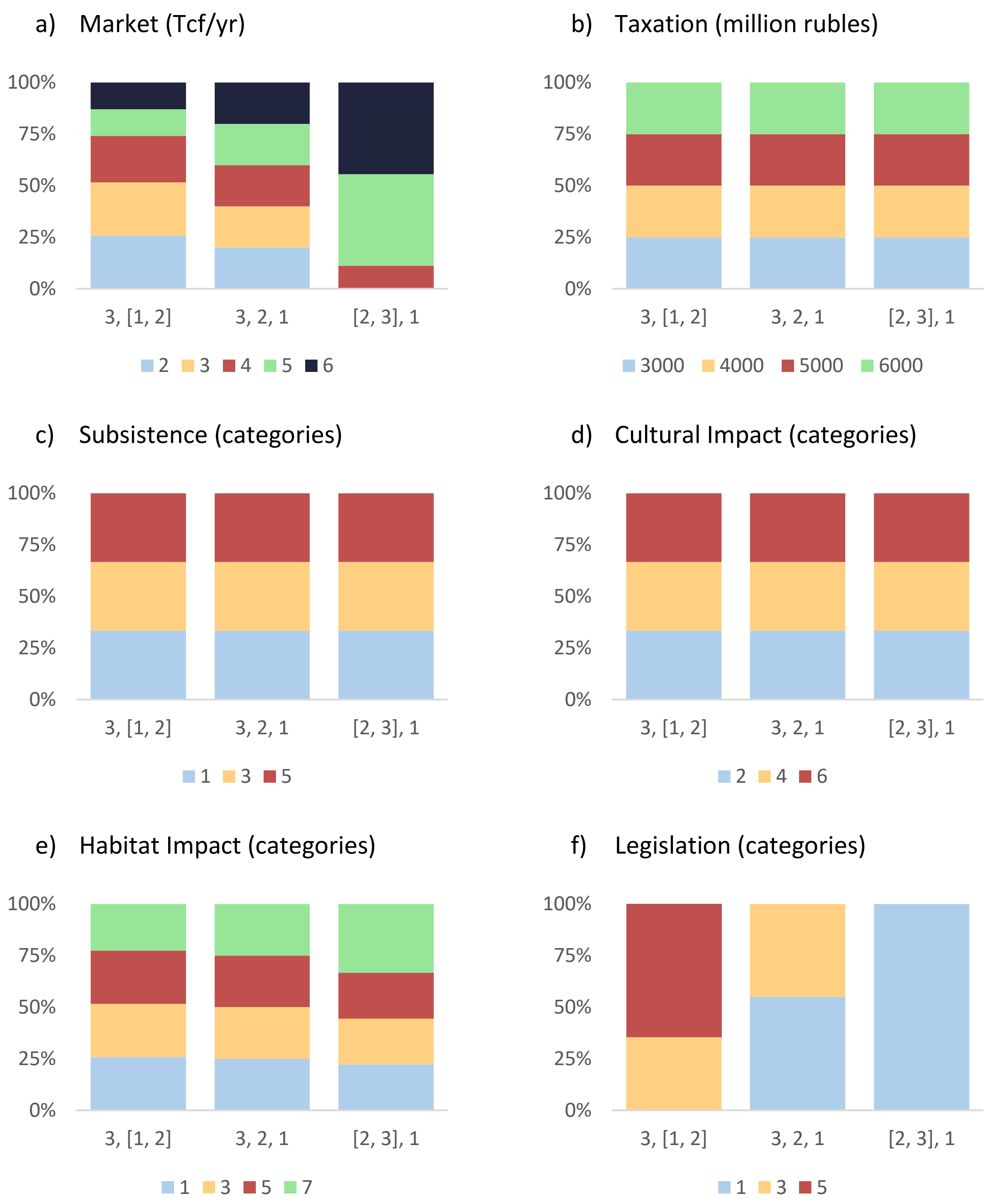


Figure 5.15 *Summary of scenario results with high social and environmental weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios.*



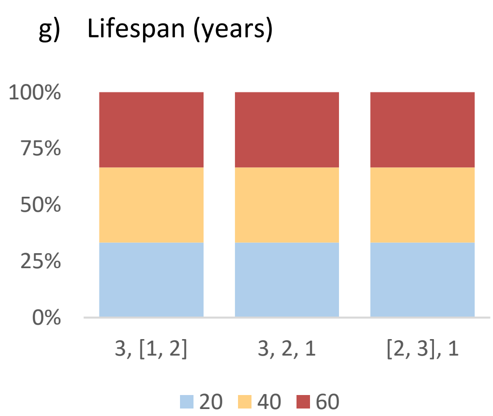


Figure 5.16 *Summary of scenario results with high infrastructure weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios.*

Table 5.12 *Summary of possible results (orange) from veto scenarios for each weighting scheme, with each column representing one weighting scheme. Square brackets indicate alternatives are equally ranked. An orange tick represents that the specified result is possible for a given weighting scheme. Other rankings that did not result from any scenario are not shown. Econ: economic; Soc/Env: Social/Environmental; Infra: Infrastructure.*

		Veto scenarios			
Weighting Scheme		Uniform	Econ	Soc/Env	Infra.
Possible Alternative Rankings	*[1, 2, 3]*	✓	✓	✓	✓
	[1,3], 2	✓	×	✓	✓
	3, [1,2]	✓	×	✓	✓
	1, 3, 2	✓	✓	×	×
	3, 1, 2	✓	×	✓	✓
	3, 2, 1	✓	×	✓	✓

In the preference only scenarios with uniform weight, alternative 1 is always ranked first, and alternative 2 is always ranked last (Table 5.11). Introducing veto thresholds removes this consistency, although alternative 2 is still never ranked as the preferred alternative alone (Table 5.12). With a low veto threshold for legislation, the performance of alternative 1 on this criterion is sufficiently inferior to both other alternatives that it is outranked overall (Figure 5.17a). With high economic weight (Figure 5.17b), most veto thresholds prevent alternative 2 outranking alternative 3, so there are only two possible results (Table 5.12), as alternative 1 has superior performance on the high weight criteria. With high social and environmental weight (Figure 5.17c), in preference-only scenarios alternative 3 ranked first, and alternative 2 ranked last. Although there are more possible outcomes when incorporating veto thresholds, these two elements remain largely true. The only possible result that does not have these alternatives ranked in this way (alternative 3, alternative 2, alternative 1) is again caused by a low veto threshold on legislation, sufficient that alternative 1 cannot outrank any other alternative (Figure 5.17c). For scenarios with high infrastructure weight (Figure 5.17d), with preference thresholds only, alternative 1 is always ranked last overall, but veto thresholds introduce results where alternative 2 is last ranked (Table 5.12). Introducing veto thresholds on environmental and social criteria are sufficient to cause alternative 2 to be outranked, due to its inferior performance across these criteria.

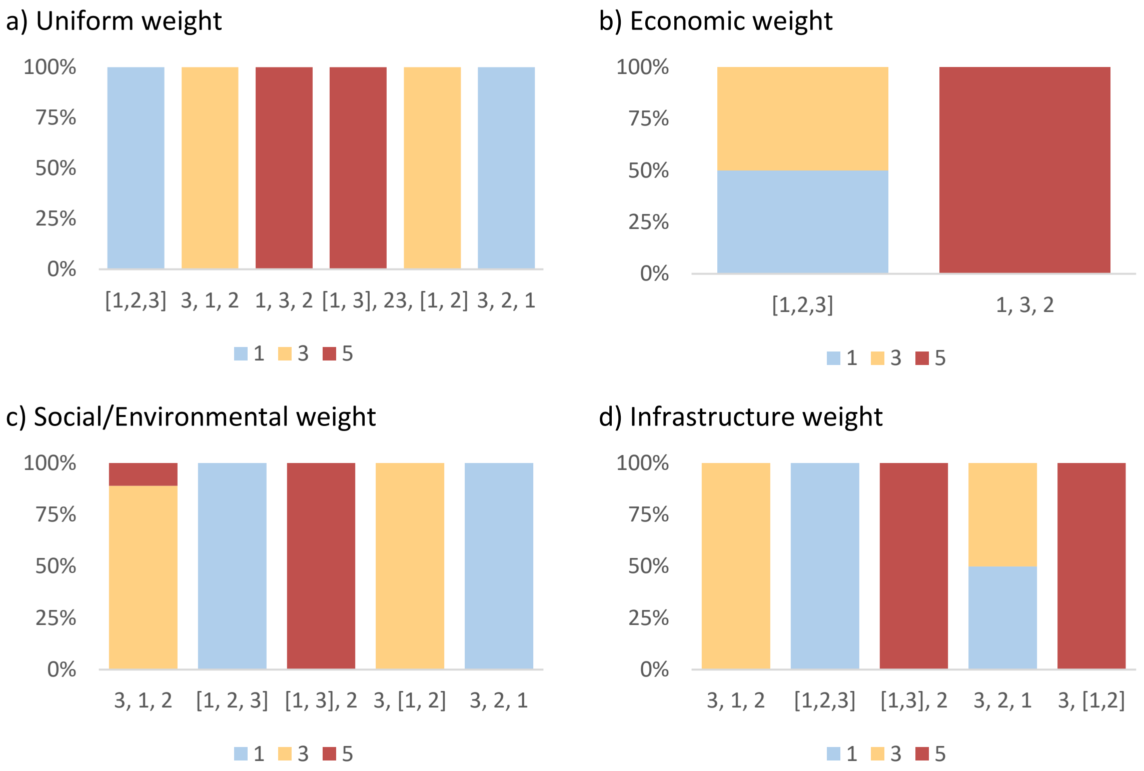


Figure 5.17 *Impact of legislation criterion veto thresholds for the four weighting schemes.*

5.3.8 Discussion

Across all scenarios, alternative 2 is never ranked as the sole preferred alternative (Table 5.11 & Table 5.12), largely due to its negative environmental and social impact compared to the other alternatives. Other large proposals for Alaska (Section 4.4) and Canada (Section 5.2) are outranked for similar reasons, suggesting that gas hydrate development in these sensitive and remote environments may not be sufficiently beneficial to justify the environmental damage. Alternative 2 ranks preferred equal with other alternatives in scenarios with high weight on infrastructure criteria, suggesting this alternative becomes viable where it has strong government support, allowing it to proceed despite negative social and environmental impacts.

Compared to the Alaskan and Canadian case studies, there are conditions at Messoyakha where large scale gas hydrate development outranks no development. As the distribution infrastructure already exists, the environmental and social impacts are much less severe in the European export case than other large gas hydrate development scenarios. However, while the negative impacts may be mitigated, the coincident conventional gas development often provides all the gas supply necessary, reducing the business case for gas hydrate. Without a detailed comparative assessment it is unclear whether conventional development projects in these Arctic environments would be recommended based upon this protocol. Over time gas hydrate may become cheaper, or less environmentally damaging than other gas sources, especially if CO_2 exchange becomes a viable gas hydrate production mechanism (Marcelle-De Silva and Dawe, 2011). If this situation occurs, the Messoyakha field may be produced ahead of other conventional gas fields in a gas-rich country such as Russia. However, whether conventional or unconventional, gas production must be sufficient to justify these impacts. In many cases, existing infrastructure was developed with fewer restrictions on environmental impact than currently apply, and maybe not be recommended if present-day legislation has to be adhered to. The protocol could be used to evaluate all resource development at a site using the same infrastructure, but gas hydrate development must be considered commercially viable first, as gas hydrate is not usually considered an economically recoverable resource at the present day by government or industrial stakeholders (Boswell and Collett, 2011).

Some criteria that were not included in this study due to data availability could alter the final result. Although difficult to speculate the impact of specific criteria for the same reason, I can draw some general conclusions. Habitat impact was the only environmental criterion considered, and all other environmental criteria would reduce support for any development alternative if included. As industrial development intensity increases, so does environmental degradation, as seen elsewhere in the YNAO (Nuttall, 2010), so more consideration of environmental impacts would likely result in more scenarios where no industrial development is the preferred alternative. Of the omitted criteria, very few would increase the preference for a development alternative, with the possible exception of multiplier effects, where gas hydrate commercialisation provides benefits to entities down the distribution network. These outcomes illustrate the importance of conducting a balanced, unbiased evaluation, as certain outcomes can be recommended by only picking criteria that consider one side of the problem.

As the Messoyakha field is connected to the Unified Gas Supply System, it is impossible to determine the precise route of gas export to Europe. As a result, it is difficult to quantify impact during transportation in this alternative, so alternative 1 will have lower evaluated impacts than alternative 2, where the specific pipeline route is known. However, as the infrastructure being used by alternative 1 is also used for conventional gas export, the impacts from this infrastructure cannot be assigned wholly to gas hydrate export. In future applications, more consideration may be paid to establishing what proportion of total impact can be assigned to new development in this situation (Section 5.4.9).

5.3.9 Conclusions

Unlike other locations considered, gas hydrate at the Messoyakha field already has infrastructure connections to distribute the produced gas. This protocol could be used to explore the best future development plan for this currently under-utilised field, whether for additional supply to Europe or as part of a western export route to China, although there are many other conventional fields in Russia where natural gas could be produced.

5.4 Nankai Trough, Japan

Japan derives 91% of its energy from fossil fuels, but lacks large domestic resources, relying on imports for over 80% of its energy needs (Oyama and Masutani, 2017). Coal and oil currently provide 66% of total primary energy, with natural gas providing 24% (Akira et al., 2018), but environmental concerns have led to recent governmental investment in natural gas over coal and oil (Oyama and Masutani, 2017). Although potentially transitioning to renewable energy in the long term, in the short term fossil fuels will continue to provide a large share of Japanese energy. Japan had invested in nuclear power, and planned to expand this energy source further as their fuel of the future (Oyama and Masutani, 2017), but public perception shifted after the Fukushima plant disaster, leading to nationwide plant shutdowns (Murakami et al., 2015) and a need for other solutions. In recent years, Japan has gradually begun to bring nuclear power plants back online in response to rising energy costs, but public opinion has not fully recovered (IGU, 2019), necessitating a diverse energy strategy. Long-term predicted energy demand is anticipated to stagnate or decline, as growth in the industrial sector slows, technology becomes more efficient, and temperature increases reduce domestic demand in winter (Akira et al., 2018). Within this decline however, overall gas demand is anticipated to remain steady or slightly increase.

Japan has little to no domestic natural gas resource. As a result, with the exception of a possible pipeline connection to Russia, Japan is predicted to remain reliant on ship-borne LNG for at least the next decade (Lochner and Bothe, 2009). Japan is currently the world's largest LNG importer and storer, and only utilises 50% of present built capacity (EIA, 2017), as it plans to continue expansion of its gas usage. Due to mountainous terrain and large urban areas, Japan lacks a nationally connected distribution network for natural gas, instead supplying local urban centres directly through their ports (Ishwaran et al., 2017). To avoid over-reliance on a single supply source, Japan has LNG import contracts with Australia, Malaysia, Qatar, and other Asian and Middle Eastern nations (METI, 2019). The prices for these contracts are linked to the oil market, leading to contract prices in excess of $10/MMBtu, above the market price in Europe and the United States (EIA, 2017). Japan's natural gas market was wholly government controlled until 1995, when the market was partially liberalised in an attempt to encourage competition and drive gas prices down (Ishwaran et al., 2017). Despite this effort, a virtual monopoly remains, with three companies (Osaka Gas, Tokyo Gas and Toho Gas) controlling over 70% of the domestic gas market

(Ishwaran et al., 2017). Market liberalisation was also partially reverted in the wake of the Fukushima disaster to effect rapid, large-scale change in energy supply (Ishwaran et al., 2017).

5.4.1 Japanese Gas Hydrate Research

Recognising its reliance on imported natural gas, Japan has long been interested in the potential of their offshore gas hydrate deposits to provide a domestic gas supply. The government established a national methane hydrate research and development program in 1993 (Oyama and Masutani, 2017), signalling the start of its development efforts. The distribution of most gas hydrate reservoirs within Japan's Exclusive Economic Zone (EEZ) has been estimated from the location of bottom simulating reflectors (BSRs) in offshore seismic surveying (Tamaki et al., 2017). In some areas the presence and saturation of methane hydrate has been confirmed by additional detailed surveying or drilling (Tamaki et al., 2017). Japan has subsequently advanced its gas hydrate commercialisation efforts on two fronts; a series of offshore drilling projects in its territorial waters in 1999/2000, 2004, 2012/13 and 2017 to evaluate the resource and identify potential commercial challenges (Tsuji et al., 2004; Yamamoto, 2015a; Yu et al., 2019); and involvement in Arctic drilling programs in Canada and the United States (Boswell et al., 2019; Yamamoto, 2015a), utilising these onshore projects as natural laboratories for production technology.

Domestic Japanese gas hydrate research has focussed on the Nankai Trough (Figure 5.18), a 1 km deep submarine trench caused by a thrust fault at the boundary between the Philippine and Eurasian plates (Tsuji et al., 2004; Yu et al., 2019). The Nankai Trough is estimated to have enough gas hydrate to meet all Japan's gas needs for over 100 years (Oyama and Masutani, 2017). Gas hydrate is found in a series of layers 270 m below the sea floor, with 40 m total net thickness (Fujii et al., 2015). Gas hydrate saturation varies based on lithology, with 50-80% hydrate saturation sandy high porosity layers interbedded with low porosity muddy layers with 0-10% gas hydrate saturation (Fujii et al., 2015). There is no free gas reservoir accompanying the gas hydrate layers (Colwell et al., 2004), hence the absence of conventional commercial efforts. Although faulted by local tectonic activity (Jia et al., 2017), the gas hydrate layers show good lateral connectivity, necessary for an effective drilling operation (Tamaki et al., 2017). The gas hydrate is almost pure methane hydrate, with a microbial origin (Colwell et al., 2004).

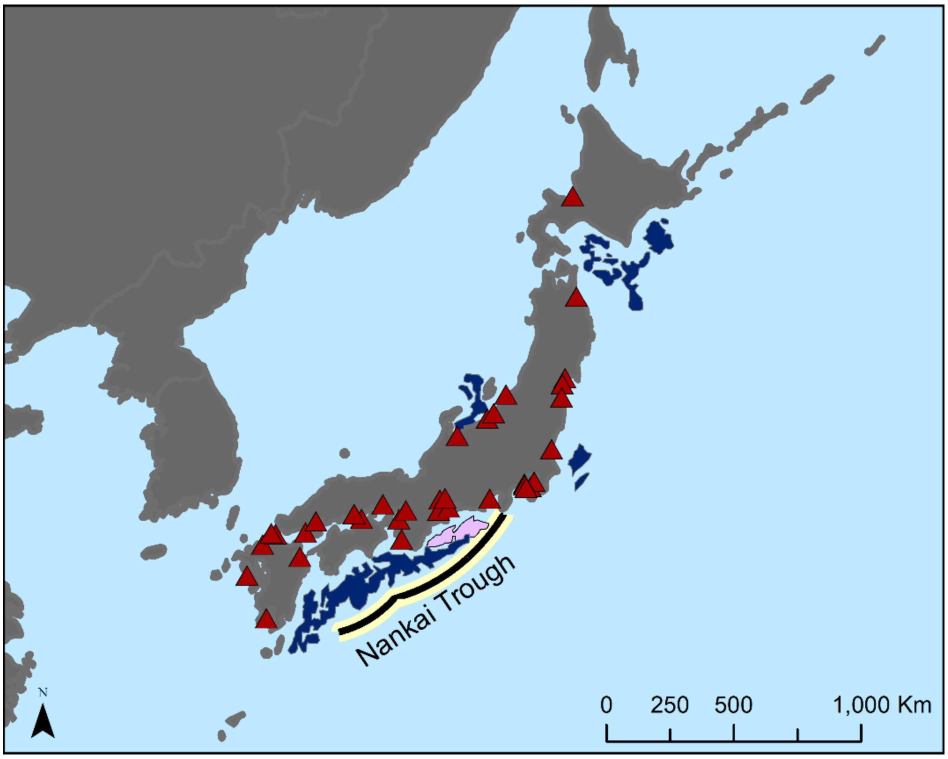


Figure 5.18 *Map of Japan showing areas with bottom simulating reflectors that suggest concentrated methane hydrate (navy) or where methane hydrate has been confirmed by detailed surveying (pink) (MH21, 2010). Red triangles are existing LNG import terminals (Ishwaran et al., 2017). Black line indicates the Nankai Trough.*

Production tests were conducted at the Nankai Trough in 2013 and 2017, using depressurisation as the gas hydrate dissociation mechanism (Yamamoto, 2015a). The 2013 test lasted for 6 days, until excessive sand production forced operations to suspend early (Yamamoto et al., 2014). In the 2017 test, the first well was terminated after 12 days again due to excessive fine sand production, an issue that was rectified before the second well test, which produced gas for 24 days before planned shutdown (Yu et al., 2019). Fine production occurs as the shallow sediment has low consolidation, and gas hydrate produces large quantities of water that wash fine material out of the formation, as well as releasing additional water previously trapped by solid hydrate (Yamamoto et al., 2019). High water production limited gas production in the second test, as water production exceeded the installed pumping system capacity (Yamamoto et al., 2019), but at each stage technology is being refined towards ultimate commercialisation.

5.4.2 Alternatives

For this case study I present two alternatives, developing and not developing gas hydrate. Japan could pursue gas hydrate development due to energy security concerns, costly import contracts, and a desire to reduce greenhouse gas emissions, as gas could displace coal and oil from Japan's energy breakdown. Alternatively, the resource derived from gas hydrate may not be sufficient to justify the cost or environmental impacts of a large-scale offshore drilling program. If gas hydrate is not pursued, Japan could continue with existing LNG contracts, while returning to nuclear power and investing in renewables to effect an energy transition, phasing natural gas out of its energy mix alongside other fossil fuels.

Annual Japanese natural gas demand since the Fukushima event has remained between 115-125 bcm/yr (BP, 2019). Forecast production estimates for a Nankai gas hydrate well under commercial conditions is 0.1 bcm/yr (Yu et al., 2019), meaning 1150-1250 wells would be required to meet Japanese gas demand wholly from gas hydrate. This production rate would require improvements on current technology, as it is an order of magnitude above the rates achieved in production tests (Yu et al., 2019), but sufficient technological refinements are anticipated before widespread commercialisation.

5.4.3 Criteria

From the set of criteria in Section 4.3.4, I choose to use the economic criteria cost (F1) and market (F3), the social criterion employment (S2) and the environmental criteria ecological integrity (E3) and unintended environmental impact (E5). As this location requires offshore development, there is no local human population in the immediate vicinity of production operations. In other settings there would be an affected human population wherever produced gas is brought onshore, but Japan already has a natural gas distribution infrastructure from LNG imports, so the impacts felt on land would not differ depending on which alternative gas source is used.

For development, estimated well spacing is 360–500 m (Kurihara et al., 2009), which gives a limit of 11,500 wells if the entire area (pink area on Figure 5.18) was developed at the wider spacing. This is an overestimate, as inconsistent resource quality and seafloor conditions will not encourage development uniformly across the area, and this spacing refers to the highest potential areas where scientific testing has occurred. This well density estimated from modelling is also highly inconsistent with other offshore field developments (McNulty et al., 2010), so I consider it an upper limit and look to refine down to realistic levels of development by comparison with existing offshore conventional oil and gas projects elsewhere. For another estimate, I consider conventional offshore operations with similar water depths and distances to shore, such as in the Gulf of Mexico (McNulty et al., 2010), and create an estimate of well numbers if offshore Japanese development followed a similar pattern. With this approach I reach a more reasonable estimate of 1500 wells to produce the Nankai methane hydrate area. Rather than creating a large oversupply, this estimate is about 20% more wells than the necessary minimum to meet demand, which allows for wells to have sub-optimum production, or temporary closures in the system for maintenance. These well numbers indicate gas hydrate production at the Nankai Trough could meet Japanese gas demand, but would not generate excess volumes of gas for export. As a result I do not include resource criteria, as the two alternatives have equivalent volumes of natural gas, just from different sources. Further geoscientific factors may be relevant, but Japan's diverse import mixture makes it impossible to isolate a single site as the supply source for the no gas hydrate development alternative.

Compared to other sites studied, there is no indigenous population where cultural sites or subsistence assets may be affected. Similarly, there are no obvious recreation assets affected this far offshore, which also negates any aesthetic impact. I do not include legislation, logistics or resource distribution as I consider supply security in my impact assessment of market, and do not want to double count the same impact, although ensuring security of supply is potentially the main driver of Japanese gas hydrate development. Both alternatives are scored against each criterion in an impact matrix (Table 5.13).

Table 5.13 *Impact matrix for Nankai Trough gas hydrate commercialisation alternatives, with the indifference value corresponding to the highest error margin on either impact estimate for each criterion. Derivation and further explanation of each impact value is given in the following sections.*

	Alternative 1	Alternative 2	Indifference
Cost ($ billion)	59	0	22
Market	0	0.24	0.1
Employment	2400	0	900
Ecological Integrity	Medium	Insignificant	1 category
Unintended Environmental Impact	Medium	None	1 category

5.4.3.1 Cost

My cost assessment quantifies necessary new investment to commence resource development. The gas supply chain includes production, processing, storage, transmission and distribution. For production, the construction cost per well is estimated at $11.5–$14 million (Kurihara et al., 2009; Uhegbu, 2014). Compared to conventional oil and gas, gas hydrates are found at much shallower depths (Merey, 2016), so could be developed using multiple smaller and cheaper vessels in sequence, rather than using a single, expensive, highly specialised drillship (Yamamoto and Miura, 2018). This approach may reduce production costs for gas hydrate. However, a gas hydrate well also has additional costs compared to a conventional gas well, due to necessary controls on fine material and water production (Yamamoto and Miura, 2018). I assume that these factors have equal and opposite effects, and so use an average cost estimate of $12.5 million per well, giving a total development cost for 1500 wells of $19 billion.

Conventional-style operations with fixed platforms connected to shore by pipeline are not recommended here due to regional faulting and seismic activity, as these technologies are designed mostly for aseismic regions (Trimintziou et al., 2015). Therefore, the most economically viable approach for producing these broad gas hydrate deposits is through automated wells connected to a Floating Production, Storage and Offloading Vessel (FPSO), which acts as a processing facility (Giavarini and Hester, 2011). Japanese companies currently build and operate FPSOs, so this technology and expertise is available in the region (Fukumoto, 2019). The upper limit for FPSO capacity is around 6 bcm/yr (EMA, 2019), meaning that 20 FPSOs would be necessary to handle all Nankai Trough gas. The cost of an FPSO varies significantly depending on specifications and refitting necessary, from $200 million to upwards of $5 billion (Nishanth et al., 2018). Choosing a midpoint in this range, at a cost of $2 billion per FPSO, I estimate total cost for 20 FPSOs of $40 billion. FPSOs would periodically offload processed gas onto shuttle tankers, to transport processed gas to existing facilities onshore. Due to the fragmented natural gas infrastructure in Japan, gas hydrate-origin gas will have to be delivered to most demand centres directly (Ishwaran et al., 2017). This system is used to supply import-origin gas throughout Japan currently, and using smaller shuttle tankers would introduce more flexibility to accommodate variable demand. As Japan has already developed storage and distribution facilities for LNG, these facilities could be used by gas hydrate, so I assume no further downstream costs for alternative 1. Therefore, I calculate total alternative 1 cost at $59 billion.

Unpredictability in the cost of a bespoke FPSO complicates defining a total error margin, but an approximation of $1 billion variation per FPSO and an error margin of $1.5 million per well leads to an overall $22 billion cost error margin.

As Japan is currently importing LNG to meet demand, continuing this process requires no additional capital investment, so there is zero cost for alternative 2.

5.4.3.2 Market

Energy security is a major issue for Japan, which only produces a small fraction of its natural resource needs. To maintain steady supplies of LNG, Japanese companies have become stakeholders in a range of projects worldwide, but this approach remains less secure than ownership of domestic resources (McLellan et al., 2013). Using import contracts, Japan imports natural gas from a wide range of countries in an attempt to insulate their domestic supply from shocks that may affect a single supplier. 11 countries contribute at least 1.5% of Japan’s LNG imports (Figure 5.19), and these range from relatively stable, local and consistent supplies, to newer, more distant suppliers with greater political risk (METI, 2019).

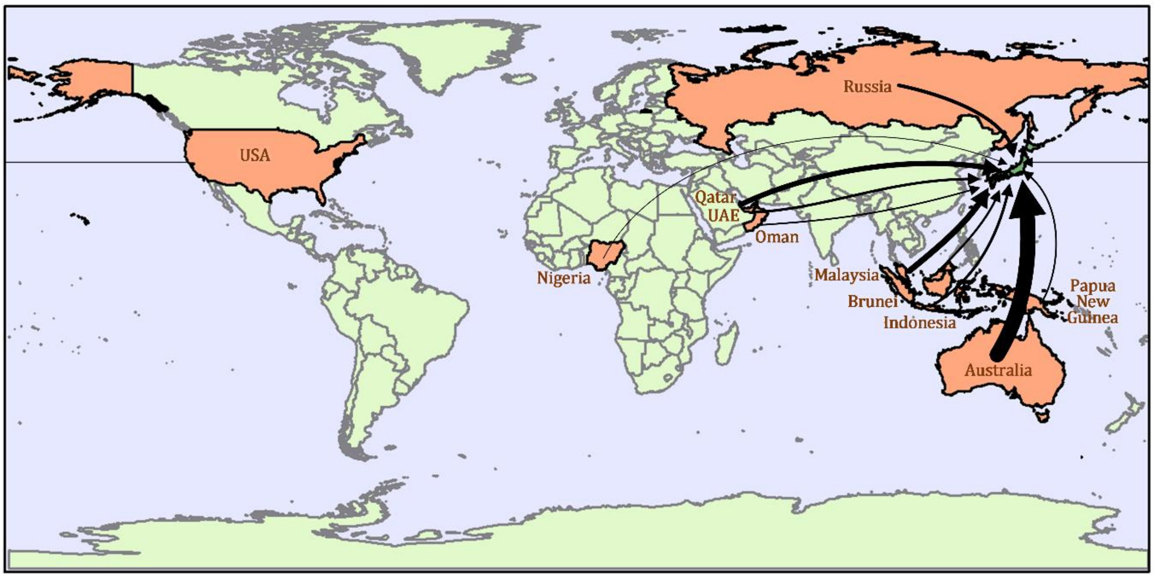


Figure 5.19 *Map of global exporters of LNG to Japan (orange), with arrows sized relative to share of total LNG imports originating from that country (METI, 2019).*

Energy security is a political issue, as continued energy supply is vital for the Japanese economy (Economides and Wood, 2009). Globally, a small number of countries control gas reserves, which often results in long supply chains with geopolitical risks originating from overarching political tensions (Economides and Wood, 2009). I quantify energy security using the Risky External Energy Supply (REES) Index, which considers supplier concentration and stability (Le Coq and Paltseva, 2009; Equation 9), a modified form of the Herfindahl-Hirschmann Index (HHI) that measures market competitiveness (Rhoades, 1993), where $REES^f$ is the REES Index for fuel f. I choose the REES index from available energy security measures (Ang et al., 2015) as it focuses on import reliance and geopolitical concerns in the countries supplying natural gas, measures risk to a specific energy source rather than the country's entire energy mix, and does not penalise Japan for creating a monopolistic supply structure by switching to wholly domestic sourcing. The REES index combines a series of relevant indices into a single measure focusing on the risk to energy security from being import dependent (Le Coq and Paltseva, 2009). As a result, the REES index aligns with the strategic aim of the Japanese government to secure its energy supply chain (Oyama and Masutani, 2017). The REES index is high where supply is distant, externally monopolised, or originating in countries with lower geopolitical stability, and reduces with any reduction in import reliance. As it is a non-dimensional index the precise value is less important than the change in value after an action, with policymakers attempting to reduce REES index values as this reduction indicates a reduction in supply risk (Le Coq and Paltseva, 2009).

$$REES^f = \left[\sum_i \left(\frac{NPI_i^f}{NPI^f}\right)^2 F_i^f r_i d_i\right] \times NID^f \times SF^f \qquad \textbf{Equation 9}$$

Where $\frac{NPI_i^f}{NPI^f}$ is the ratio of imports of fuel *f* (in this case natural gas, *ng*) from country *i* to total imports of fuel *f*, F_i^f is the fungibility of imports of fuel *f* from country *i*, r_i is the political risk index of country *i*, d_i is a measure of import distance from country *i*, NID^f is the import dependency (percentage of total consumed fuel that is imported) for fuel *f*, and SF^f is the market share of fuel *f*. I use 2018 energy data (METI, 2019) to identify the share of the natural gas import market for each supplier, as well as the total share of the gas market that is imported (NID^{ng} = 97.5%) and natural gas' share of the total energy market (SF^{ng} = 23.4%). Fungibility of imports measures the import technology used, and how easy it is to substitute one supplier for another. Since all gas supplies to Japan are tanker based, F^{ng} = 1 for all countries, as tanker supplies from any exporter are readily substituted by tankers from any other origin (Le Coq and Paltseva, 2009). For political risk, I follow the IEA's approach (IEA, 2007), averaging the World Bank's Worldwide Governance Indicators for political stability and regulatory quality (Figure 5.20a), scaled to give a value between 1 and 3 by calculating a simple average of both indicators, then redistributing calculated values to the new range, with higher values indicating higher risk (Figure 5.20b; Kaufmann and Kraay, 2019). Political stability measures the likelihood of the current government being violently and suddenly ousted from power, which would be highly disruptive to its international relations and trade, and regulatory policy measures the presence of policies that restrict the trade market (IEA, 2007). For the 2.1% of Japanese gas supplies listed with "other" as their origin, I use an average of worldwide indices (r_{other} = 2). Import distance is measured as the distance (in thousands of nautical miles) between gas origin and Japan, rounded to the nearest thousand to account for differences in travel distance to different ports in Japan. Where no specific origin is given, I use an average of distances for all other importers (d_{other} = 5000 nautical miles). To calculate an error margin I vary the political risk values and calculate how this effects REES index.

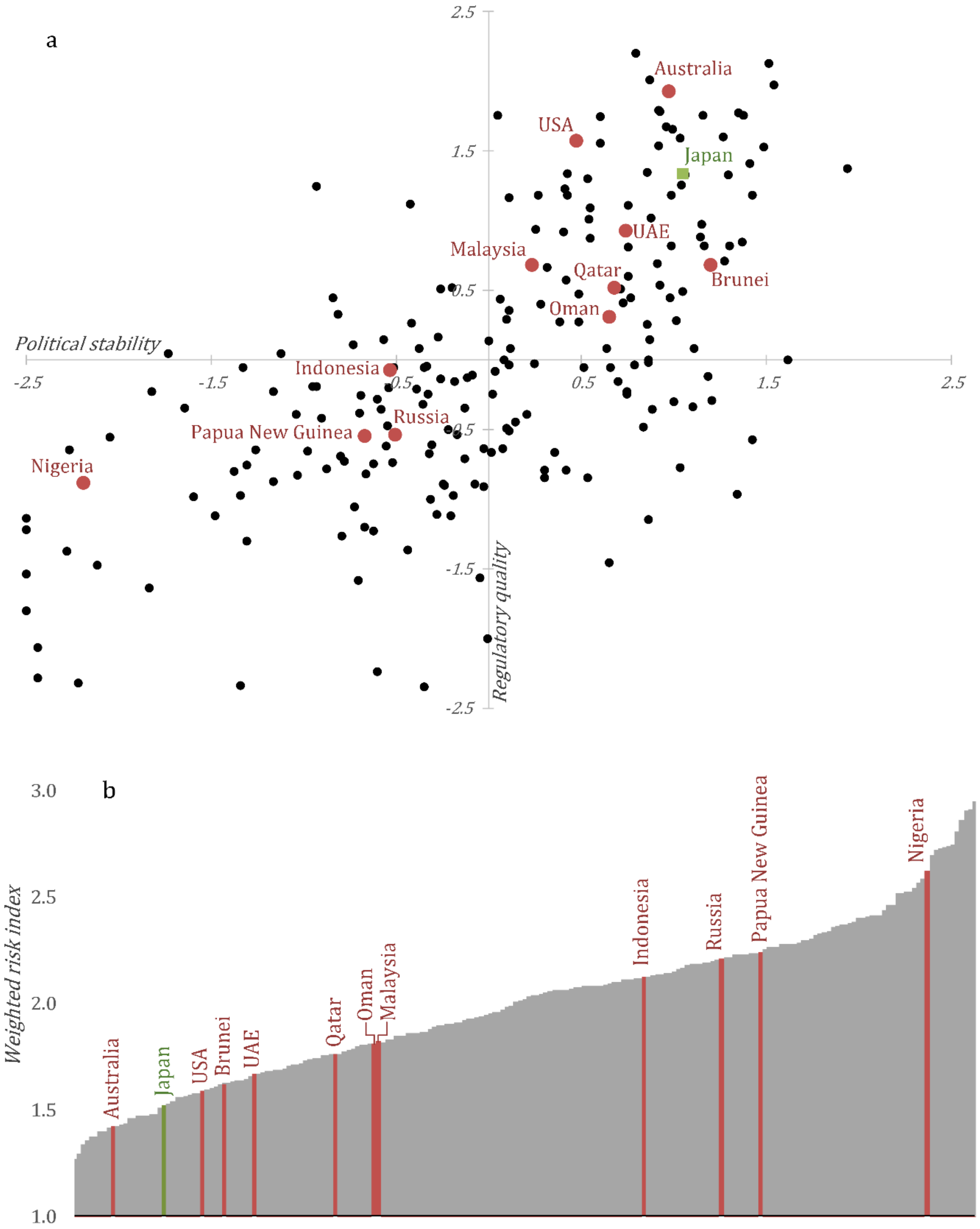


Figure 5.20 *a) Plot of World Bank's Governance Indicators for political stability (x-axis) against regulatory quality (y-axis) for all countries (Kaufmann and Kraay, 2019). For both indices higher values indicate better performance. b) Plot of scaled governance indicators for all countries, where higher values now indicate a higher risk. On both plots countries that Japan imports gas from are highlighted in red, and Japan itself is highlighted in green (METI, 2019).*

Overall, Japan is evaluated as a more stable country than almost all countries it imports from (Figure 5.20), so stands to benefit significantly from reducing its reliance on fuel imports. Additionally, as Japan has historically controlled its gas market, domestic supplies reduce externalities and allow Japan to more effectively regulate the price domestic consumers pay, giving Japan more control over its own economy. Natural gas has a REES Index value of 0.24, which is significantly lower than the REES indices for oil (1.20) and coal (0.76) in Japan. The REES index is primarily controlled by market share (SF^f), and oil provides 39% of Japanese primary energy, compared to 25.1% for coal and 23.4% for natural gas (METI, 2019). The REES for oil is also elevated because Saudi Arabia is a major supplier, and the governance indicators for Saudi Arabia indicate it is significantly below average for political stability. Additionally, 80% of Japanese oil is imported from four Arabian nations (Saudi Arabia, UAE, Qatar, Kuwait), so the REES index value reflects the large import distance, whereas both coal and natural gas are partially supplied from Australia and south-east Asia, with shorter transit distance. For coal, Australia provides 71.5% of total coal imports, creating a risky monopolistic market, as Japan is not well insulated from shocks in Australian supply. Therefore, any gas substitution of coal or oil would also benefit Japanese energy security, which could provide motivation for expanded gas hydrate development in future. I only consider gas hydrate substituting imported gas in this analysis.

5.4.3.3 Employment

Developing gas hydrate as a domestic resource creates employment opportunities in the resource extraction sector that are not available when the resource is imported. FPSO staffing levels vary from 30–70 people, depending on the number necessary for operation, servicing and modifications (Llewelyn, 2011). Crews rotate, so for each vessel there is a second crew of the same size to ensure year-round operations (Inniss et al., 2016). Estimating two 50 person crews for each, total FPSO employment is 2000 persons.

Tanker crew size varies between 15–25 people depending on tonnage, registration, and specific operational requirements (Wichester et al., 2006). I use the standard estimate of one tanker per FPSO to ensure a continuous gas supply, although there may be ways that supply can be optimised to use fewer tankers (Jiang et al., 2018). As a result, shuttle tankers used in gas hydrate production would employ approximately 400 persons overall. As the produced gas still requires processing and distribution, current jobs associated with the downstream LNG supply chain would be conserved, but I do not predict additional jobs in this sector.

In addition to offshore roles, Japanese gas hydrate development is being driven by the government in the form of JOGMEC, an agency created to secure continued resource supplies to Japan (Oyama and Masutani, 2017). At present this agency only has 615 employees to cover all hydrocarbon resources, mineral resources and pollution control (JOGMEC, 2019), and a major offshore development for gas hydrate in Japanese waters would likely require government oversight. These positions could also be filled through reorganisation or wider governmental restructuring, so are too uncertain to be included in my employment estimate.

While the field is developed there would be a temporary increase in employment to drill wells and establish a producing field. Average crew numbers for offshore technology are 55 per offshore rig, 80 per seismic vessel and 80 per drillship (Inniss et al., 2016). Drilling a well offshore takes approximately 30 days (Kaiser, 2009), so drilling completion of this field would be a multi-year process. In keeping with the other case studies presented in this thesis, I do not include temporary positions in my employment estimate, as the benefit they provide is limited, but the large development size in this case may create longer duration temporary positons that provide relatively stable employment and income.

Due to the large necessary growth in offshore development coupled with an aging population, there may be insufficient skilled workers to fill all new positions (Ganelli and Miake, 2015). Japan has a low unemployment rate (2.2%), and already struggles to fill existing job vacancies as a result (Kyodo News, 2019). To combat this issue, the Japanese government has focussed on encouraging immigration of skilled labour, but Japanese corporations have been less successful in making opportunities attractive to external talent (Oishi, 2012). Therefore, in this study job creation may not be as beneficial as in other locations, and may instead be a limiting factor on development. I consider this possibility further during scenario simulation (Section 5.4.6).

5.4.3.4 Ecological Integrity

To evaluate ecological integrity I consider by-products of gas hydrate production that may damage the ecosystem. There are two primary sources of pollution to the water column, methane originating from the well or surrounding seafloor, and discharge of treated water from production (Arata et al., 2009). This methane leakage will enter the water column, but it is highly unlikely to reach the atmosphere (Ye et al., 2018), so I only consider impact on the marine ecosystem.

Production technology used for gas hydrate will be similar to that in conventional gas wells, so gas leakage from the well, as seen in conventional natural gas production, is a potential issue (Nagakubo et al., 2011). Well failure rates are highly variable depending on location, although modern wells are generally less likely to fail (Michanowicz et al., 2017). Methane leakage is estimated between 0.4-10% of production in conventional operations from source to end use, although the top end of this range refers to older systems that have degraded (Sanchez and Mays, 2015). Using unconventional shale gas production in the contiguous US as an analogous recent gas development, 2.5-3.5% of these wells have experienced some form of integrity failure (Davies et al., 2014). The US EPA estimates around 2.4% of gross US natural gas production is leaked from the production and distribution infrastructure system annually (Alvarez et al., 2012), so gas leakage is highly likely even in a new system. The Japanese seafloor shows a faulted turbidite sequence, where high permeability sandy layers and thrust faults could both act as possible fluid conduits (Yoneda et al., 2015). Active fluid seeps have been identified, that may be discharging local biogenic methane, or fluids with a deeper origin (Henry et al., 2002). Once methane is released in a commercial project, some produced gas may preferentially migrate upwards through these high permeability pathways, rather than migrating laterally to the well where it can be captured (Riley et al., 2019). In addition to these specific pathways, the overlying sediment seal is a mixture of clays and silts (Yamamoto et al., 2014), with lower permeability than the hydrate bearing layer. In this setting, gas hydrate dissociation may cause overpressure that can fracture any overlying seal (Grozic, 2010). Once released to the water column, methane can react with dissolved oxygen in seawater to form CO_2 (F. Wang et al., 2018). On a large scale this reaction causes the marine environment to become anoxic, inhibiting plant and animal growth (F. Wang et al., 2018). As small species succumb to oxygen stress first, the local environment becomes a mortality sink where predator species concentrate, further stressing local populations (Partain, 2015). Methane in the water column also induces ocean acidification (Biastoch et al., 2011), which can influence the reproductive capacity of some species, and is especially damaging to calcifying organisms (Zhao et al., 2017). The deep ocean is a very low energy environment, so any pollution created would take a long time to disperse and leave the system (Partain, 2015).

Despite these potential impacts, methane release in commercial production is estimated to have very localised impacts, and cause limited change to the local ecosystem (Nagakubo et al., 2011). Under experimental conditions, dissolved methane did not reach sufficiently toxic concentrations to affect the growth or mortality of Nankai Trough microfauna, but potential toxicity remains at greater depths where the maximum dissolved methane concentration increases, or at higher trophic levels where methane may accumulate to toxic concentrations (Hirata et al., 2013). Data from operational production is temporally limited to short duration production tests, such as the 2017 South China Sea test, where no increase in water column or ocean bottom methane was detected over the 60 day test duration (Li et al., 2018). Without field testing there are currently no indications that high methane pollution is likely during production, although commercial projects are estimated to have higher fluid flow rates over longer durations.

Further complicating this environmental impact assessment, methane release is not anticipated to be wholly negative to the ocean ecosystem. Methane flows may disturb subsurface sediment and nutrients, mixing these into the water column, which is especially useful for local fauna in a low energy, deep-ocean environment (Hovland et al., 2012). In other environments, natural methane seeps show greater biomass and species richness than the surrounding areas (Åström et al., 2016), so while unrestricted methane input is not suggested, small volumes of methane may improve local growth conditions. Some areas of the Nankai wedge already have active methane seeps, suggesting local fauna will be largely unaffected by moderate additional methane input (Henry et al., 2002).

In addition to methane discharge, methane hydrate dissociation also produces large volumes of fresh water (Sun et al., 2016). In commercial operations, produced water will be treated to minimise environmental impact before being discharged into the water column (Arata et al., 2009). As methane hydrate dissociation produces fresh water, discharging produced water will affect local salinity (Arata et al., 2009). Water can be discharged at any depth in the water column, and will most likely be released at shallow depth, a high energy environment, from where it will rapidly diffuse (Ishihara et al., 2008). There has yet to be a field investigation of the impacts of commercial-scale water production into the water column, but current modelling suggests that produced water will hardly influence marine organisms in the surrounding ocean (Arata et al., 2009; Ishihara et al., 2008).

Both alternatives rely on tanker shipping to supply gas to Japan. Tanker shipping discharges toxins, which become especially concentrated near ports (Ng and Song, 2010). Ships also cause noise and atmospheric pollution (Andersson et al., 2016), impacting a wider ecosystem than submarine pollutant discharge. The cumulative environmental impact of shipping is higher for alternative 2, as foreign tankers must travel 1-2 orders of magnitude further to reach Japan, but ecological impact is spread over this entire route, rather than concentrated at a single point. Intercontinental travel also accentuates the risk of transporting invasive species, which can be especially damaging for local species populations (Andersson et al., 2016). Wherever gas originates in alternative 2 will also experience ecological impacts from gas production but, unless a project only supplies Japan, it is difficult to quantify the ecological impact of alternative 2. Therefore, I consider shipping as ecologically damaging for both alternatives, but pollutants in the water column from gas production are only considered for alternative 1.

To assign environmental impact I calculate a risk index (van Lenteren and Loomans, 2006). This index has two parts, with qualitative scales for probability (Table 5.14a) and magnitude of adverse impact (Table 5.14b), the results of which I combine into a single evaluation of level of risk (van Lenteren and Loomans, 2006). There are four possible levels of overall environmental risk (insignificant, low, medium, high; Figure 5.21). I consider three environmental risks, methane release (M), produced water release (W) and shipping pollution (S), and qualitatively evaluate probability and magnitude in each case using available literature and modelling.

Table 5.14 *Qualitative a) probability scale and b) magnitude scale, with definition of each term (van Lenteren and Loomans, 2006).*

a)

Very Unlikely	Not impossible but only occurring in exceptional circumstances
Unlikely	Could occur but is not expected to occur under normal conditions
Possible	Equally likely or unlikely
Likely	Will probably occur at some time
Very Likely	Is expected to occur

b)

Minimal	Insignificant environmental impact
Minor	Reversible environmental impact
Moderate	Slight effect on native species
Major	Irreversible environmental effect but no species loss, remediation possible
Massive	Extensive environmental effects

Mitigating actions will be taken to limit methane release into the water column, but a leak is still probable over the project lifespan (probability = likely). Due to the complex relationship between methane and the water column, methane input is unlikely to cause major environmental damage, but may affect native species used to a lower methane environment (magnitude = moderate). Water release will occur to accommodate the high volumes of produced water (probability = very likely). However, the environmental impact of introducing properly treated water that rapidly diffuses is negligible (magnitude = minimal). Finally, shipping is a high polluting industry necessary for gas supply in both alternatives (probability = very likely). The variety of pollutants may irreparably damage the environment, but remediation could take place if shipping ceased (magnitude = major). Although shipping has more impact in alternative 2, it is not sufficient to change the magnitude classification, and even if it were the resultant risk would not change (Figure 5.21).

To qualitatively evaluate total ecological impact, I transform each qualitative risk level to a numerical value (insignificant = 1, low = 2, medium = 3, high = 4), with a value of zero used where the associated impact does not occur (Table 5.15). I then average these values and round to the nearest whole number, which corresponds to an overall qualitative risk (Table 5.15).

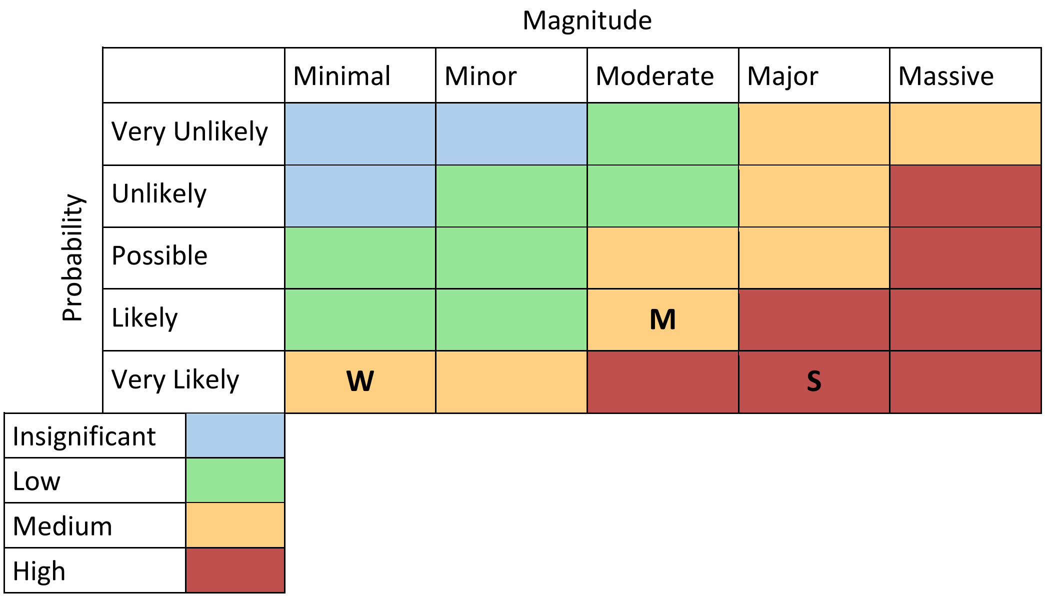


Figure 5.21 *Risk assessment plot of impacts of methane release (M), water release (W) and shipping (S) (van Lenteren and Loomans, 2006).*

To determine error, I calculate potential environmental risk if each impact is allowed to vary by one category in either magnitude or probability (Figure 5.21). Shipping continues to have a high risk if allowed to vary by one category in any direction, so there is no associated error margin for the qualitative impact assessment of alternative 2. For alternative 1, increasing methane risk to high causes an increase in overall impact to high, so I define a total error margin of one category.

Table 5.15 *Summarised risk scores and overall ecological impact for each alternative.*

	Alternative 1	Alternative 2
Methane release	Medium (3)	- (0)
Water release	Medium (3)	- (0)
Shipping	High (4)	High (4)
Overall	**Medium (3)**	**Insignificant (1)**

5.4.3.5 Unintended Environmental Impact

Gas hydrate production will remove solid hydrate and create mobile phases, changing the mechanical and hydraulic properties of the sediment (De La Fuente et al., 2019a). Two geomechanical issues have been suggested for gas hydrate production in the shallow submarine subsurface, subsidence and slope failure (Partain, 2017). I consider available monitoring and modelling data to evaluate if these hazards are likely at the Nankai Trough.

Depressurisation may result in increased local effective stress that causes sediment compaction (Sun et al., 2019). The same low permeability sediments that limit upward gas migration and loss will increase the risk of sediment failure, as pore fluid overpressure may increase, reducing sediment strength (Grozic, 2010). Additionally, fluid mobilisation in gas hydrate production removes solid hydrate and fine sediment, undercutting material which can then collapse (De La Fuente et al., 2019b; Lu et al., 2018). High sand production has impacted production testing, so the same subsurface material mobilisation is anticipated in any long-term production (Yamamoto et al., 2014). Subsidence is a known challenge with some conventional oil and gas projects (Nagel, 2001), and this experience can inform infrastructure design to minimise failure risk. Field scale development may cause widespread subsidence, as each well will affect a conical area centred on the well that extends beyond the subsurface area of gas hydrate dissociation (Matsuda et al., 2016), with subsidence decreasing with increasing distance from the well. As gas hydrate deposits are shallower than conventional oil or gas, surface subsidence is more likely in gas hydrate production, as poorly consolidated overlying sediments are not stiff enough to resist subsistence when the gas hydrate layer compacts (Akaki and Kimoto, 2017). A greater risk than uniform subsidence is differential subsidence, as this can induce potentially damaging tilt and torsion on equipment (Yamamoto, 2015b). Although less likely than uniform subsidence, lithological or mechanical variation may cause localised subsidence variation. One year of production is estimated to cause anywhere from 30 cm to 2 metres of subsidence (Matsuda et al., 2016; Yoneda et al., 2019). Subsidence increases with the number of producing wells (Jin et al., 2019), so subsidence in a long-term, multi-well commercial project would be larger than that experienced in any single production test, but experimental and field results are needed to quantify subsidence precisely.

Submarine slope failure is a frequent risk offshore of Japan, due to high regional seismicity (Ikari et al., 2011). Removing methane hydrate weakens the subsurface, making it less resistant to future earthquakes (Akaki and Kimoto, 2017). Convergent margins such as the Nankai Trough form areas of steep and irregular topography that are prone to many landslides (Kitamura and Yamamoto, 2012). Submarine events at active margins tend to be smaller than those at passive margins due to frequent seismicity (Kitamura and Yamamoto, 2012), but slope failure in a small event often creates a scarp that has a steeper slope than its surroundings, and so is more likely to fail in a subsequent event (Ikari et al., 2011). Also, small events may cause dynamic compaction of sediments if they do not fail, making them more resistant to other small events and loading material for large scale failure in a large earthquake (Strozyk et al., 2010). If sufficiently destabilised, in areas of sloping topography, methane-induced sediment weakening may theoretically cause a rapid, large-scale event, such as a submarine landslide (Arata et al., 2009). Likelihood of slope failure increases with increasing slope angle (Nixon and Grozic, 2007). The projected production area includes the Kumano Basin (Figure 5.18), a forearc basin overlying the Nankai Trough with little topography (Jia et al., 2017), but this is bounded by areas where the slope angle can exceed 10° (Figure 5.22), increasing risk of naturally induced slope failure (Ikari et al., 2011). Surveys of current bathymetry show evidence of numerous prior slope failures (Lackey et al., 2019), but there is currently little built infrastructure to be damaged. Once resource extraction begins, any new equipment will risk displacement or impact damage.

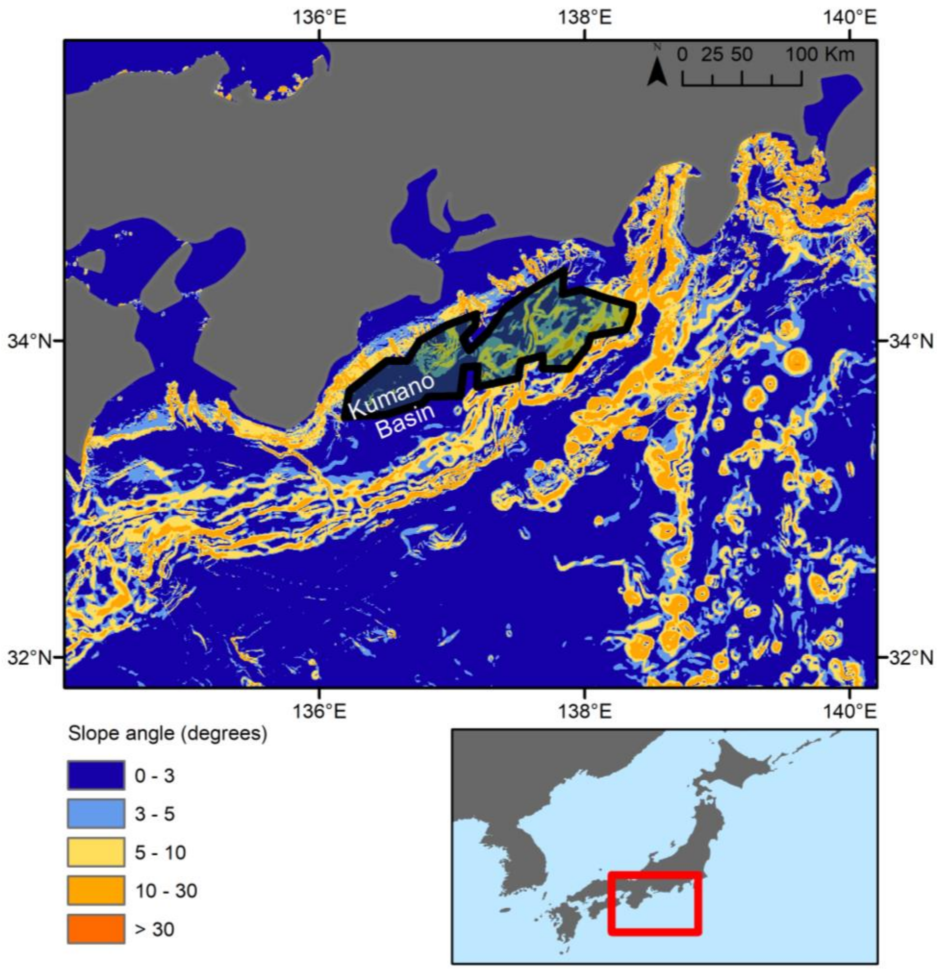


Figure 5.22 *Map of submarine slope angle in the southern BSR area, with the likely development area outlined in black (GEBCO Compilation Group, 2019).*

To assess the impact of hydrate dissociation on slope stability, I consider the factor of safety, which is the ratio between the maximum load possible before a system fails and the current anticipated load (Möller and Hansson, 2008). Values below 1 indicate a system that will fail (Möller and Hansson, 2008). The offshore Japanese gas hydrate deposits are in water depths of 1–4 km, with slope safety increasing with increasing depth due to greater sediment consolidation and confining pressure (Nixon and Grozic, 2006). Increasing hydrate content corresponds to increasing safety, so gas hydrate dissociation theoretically makes slope failure more likely (Nixon and Grozic, 2006). While both these factors suggest gas hydrate may play a role in slope instability, numerical simulation indicates that gas hydrate dissociation decreases factor of safety by less than 10%, and factor of safety would not decrease sufficiently for slope failure independent of an external trigger (Yamamoto et al., 2015). Therefore, while gas hydrate dissociation may change subsurface properties, it is unlikely to create additional failures.

I assess unintended environmental impact similarly to ecological impact, using probability and severity definitions (Table 5.16) that are standards for engineering applications (Modarres, 2016). I consider three risks, uniform subsidence (US), irregular subsidence (IS) and slope failure (SF), focussing on how gas hydrate dissociation in a commercial project would contribute to each. I plot each impact on a risk matrix to determine overall risk (Figure 5.23).

Table 5.16 *Qualitative a) probability scale and b) severity scale for unintended environmental impacts, with definition of each term (Modarres, 2016).*

a)

Incredible	Act of God
Improbable	Very unlikely to occur, can be assumed that it will not be experienced
Remote	Unlikely, but possible to occur over equipment lifespan
Occasional	Likely to occur within the lifespan of an operation
Probable	Likely to occur multiple times in the lifespan of an operation
Frequent	Likely to occur often during an operation

b)

Negligible	Impacts can be ignored
Marginal	Minor damage confined to one section of the system
Critical	Major system damage across multiple sections of the system
Catastrophic	Total system loss

Uniform subsidence is a likely consequence of gas hydrate development in this environment (probability = probable), but should accordingly be mitigated by design, and will only cause damage if subsistence significantly exceeds predictions (severity = marginal). Irregular subsidence is less likely in accordance with modelling (probability = occasional), but may be more impactful, although subsidence will likely only have localised impacts (severity = marginal). Slope failure could have more severe impacts and potentially cause more widespread damage (severity = critical), but slope failure is a natural occurrence in this region, and gas hydrate production will only marginally decrease slope stability and barely influence hazard risk, so a hydrate-production-triggered slope failure is unlikely (probability = remote).

I average these risks to reach an overall medium risk evaluation of unintended environmental impact for alternative 1 (following the same approach as used for ecological integrity). When defining total risk, another approach would be to use the highest possible risk as representative, or assigning higher risks more weight in defining an overall value, and different approaches would give different results. Additionally, these values are assigned from the impact definitions in a relatively limited range of numerical studies, which provide the best estimates available, but further study and site testing would allow these values to be better constrained. Pressure coring has been used in previous field testing (Yoneda et al., 2017), and should continue to improve geomechanical parameterisation through repeated field tests throughout the Nankai Trough area. To determine potential error as a result of limited or imprecise information, I allow each impact one degree of variation for probability or severity, which results in overall calculated unintended environmental impact levels varying from low to high, corresponding to an error margin of one category. This error margin also accommodates variation if a different aggregation method were used for total unintended environmental impact.

The inability to isolate all conventional gas production for Japan results in assignment of no unintended environmental impact for alternative 2.

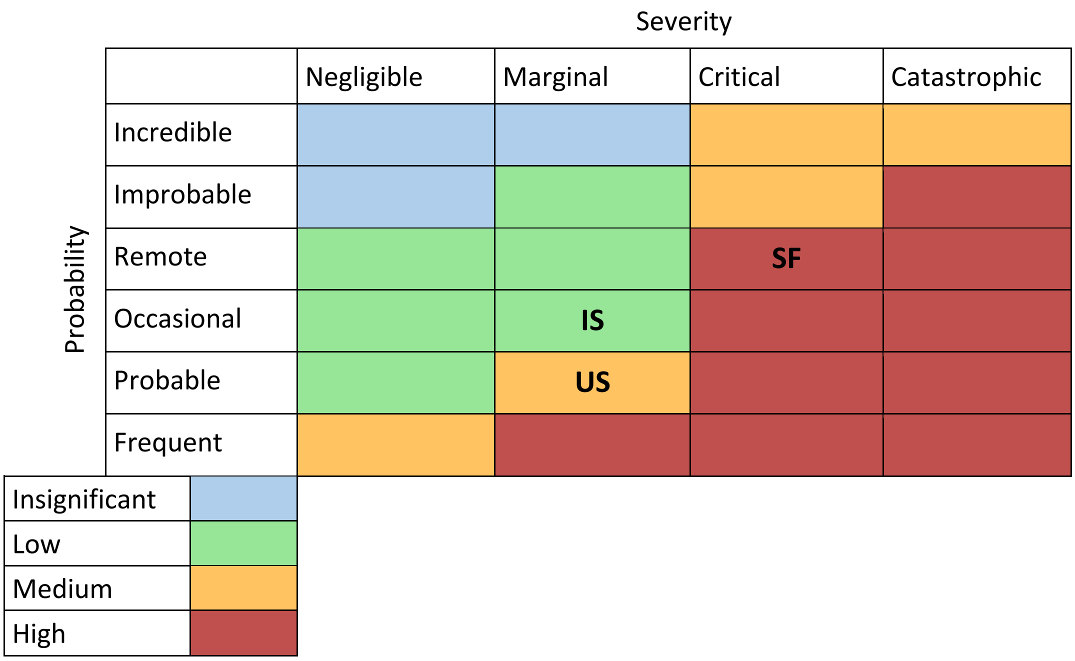


Figure 5.23 *Plot of impacts of uniform subsidence (US), irregular subsidence (IS) and hydrate-production-triggered slope failure (SF) in risk assessment matrix (Modarres, 2016).*

5.4.4 Stakeholders

As I did not engage with stakeholders on site, and this site is a significant departure from my Alaska fieldwork experience, I suggest possible representatives for future stakeholder input. I base this list on my six stakeholder groups (industry, government, indigenous groups, local community, environmental NGOS, scientific community):

Industry: For industry, there would be companies looking to develop the resource, process the resource, transport it from site to mainland, and then distribute the gas throughout Japan. Japan's natural gas market is only partially liberalised, with significant government control (Ishwaran et al., 2017), so stakeholders would originate from one of the few monopolistic companies in the market (Osaka Gas, Tokyo Gas and Toho Gas). Employees of these companies, whether sourced regionally or internationally, would also be in this stakeholder class.

Government: Japanese gas hydrate development has been driven by the Ministry of Economy Trade and Industry (METI) and the Japan Oil, Gas and Metals National Corporation (JOGMEC), both of which are government entities (Yamamoto et al., 2014). These organisations have been involved with testing in Japanese waters and tests in Alaska (Boswell et al., 2017b) and Canada (Dallimore et al., 2005), and have a strategic interest in continued resource exploration. Therefore, these government organisations would provide a range of experienced stakeholders.

Indigenous groups: Establishing members of the indigenous population of Japan is more challenging than at other sites, as Japan has historically presented itself as ethnically homogeneous (Weiner, 2009). The Ainu are an indigenous group traditionally dwelling in northern Japan who have struggled for recognition and inclusion in national debate (Siddle, 2012). Similarly, in the Okinawa islands in the extreme south of Japan, Okinawan culture is largely not recognised or compatible with broader Japanese policy, and so given limited weight in policy decisions (Hein and Selden, 2003). Other groups exist within Japan, such as the Burakumin, that are not racially distinct, but originated historically through a class system, and may experience discrimination and reduced decision power as a result (Weiner, 2009). Although these indigenous groups are not spatially coincident with development, as seen at other sites, their opinion should still be sought if they are potential gas end users, especially if they are typically poorly represented in policy debates.

Local community: Gas hydrate development offshore is spatially separated from any human community. As a result, local community stakeholders would only concentrate on the end users gas is supplied to. As this project aims to meet national gas demand, there would be many such communities whose representatives could be considered stakeholders.

Environmental NGOs: NGOs exist throughout Japan, but are often excluded from the decision-making process (Foljanty-Jost, 2005). Many of these organisations only have local to regional focus, but they are linked nationally through networks such as the Kiko Forum, which allows these NGOs to gain lobbying power by working as a single entity (Glazer, 2017). Global environmental NGOs such as Greenpeace and the WWF are active in Japan (Foljanty-Jost, 2005), so would be well placed for consultation in advance of any development.

Scientific community: Japan is a world leader in gas hydrate development and production technology, so potentially stakeholders from the scientific community are wide and varied. The National Institute of Advanced Industrial Science and Technology (AIST) has been the major research partner of offshore production testing (Yamamoto et al., 2014), and includes a methane hydrate research laboratory. Otherwise, gas hydrate is researched in varying contexts at universities throughout Japan, such as Kyushu, Tokyo and Kyoto (Jia et al., 2017; Matsuda et al., 2016; Tsuji et al., 2004), so there are many potential scientific stakeholders.

5.4.5 Weighting

I used hypothetical weighting to estimate stakeholder preferences. With only economic, social and environmental factors, I base weights on my fieldwork in Alaska. The Alaskan case study also included resource criteria, but otherwise the criteria set is sufficiently similar that weights may be appropriate to transfer. In Alaska, society divided into two groups, one prioritising economic criteria and the other prioritising social and environmental criteria. Therefore, I create three weighting schemes using this division (Table 5.17). In the first weight set, equal weight is given to the economic criteria and the environmental/social criteria. The two remaining weighting schemes are extreme positions, where 75% of total weight is given to one side of the problem.

Table 5.17 *Criteria weighting schemes used to represent hypothetical stakeholder positions for offshore Japan development.*

	Homogenous weights	*Economic prioritised*	*Environmental/ Social prioritised*
Cost	1.5	3.75	1.25
Market	1.5	3.75	1.25
Employment	1	0.8333	2.5
Ecological Integrity	1	0.8333	2.5
Unintended Environmental Impact	1	0.8333	2.5
Weight percentages			
Economic	50	**75**	25
Social & Environmental	50	25	**75**

5.4.6 Thresholds

Without stakeholder input, I use MCDA-ULaval software (Abi-Zeid et al., 2015) for scenario analyses with a range of threshold values, to explore how variation in these values impacts the final decision ranking. In the first set of scenarios, a range of preference threshold values (Table 5.18) is chosen to encompass the entire range of possible preference relationships between alternatives. For more explanation of indifference, preference and veto thresholds, see Section 5.2.4. Veto thresholds are omitted from this scenario set to explore the effect of preference thresholds only. In total I run 1024 preference scenarios for each of the three weighting schemes, one for each possible threshold combination.

In the second scenario set, preference thresholds are set at the lowest value from the previous scenarios, and veto thresholds are allowed to vary over the remaining threshold range (Table 5.18). This results in 243 scenarios with varying veto thresholds.

The two qualitative criteria use a 5 category scale to define impact (none, insignificant, low, medium, high), so threshold values indicate the difference in number of categories, e.g. a thresholds of one category would be the difference between low to medium impact, or none to insignificant etc... Because employment can be considered both positive and negative at this site I run each scenario set twice, once where employment is considered beneficial and so aims to be maximised, and another where employment is a limiting factor on development that aims to be minimised.

Table 5.18 *Range of Preference thresholds and Veto thresholds used with the impact matrix (Table 5.13) for ELECTRE III scenario analysis.*

	Preference	Veto
Cost ($ billion)	[25, 50, 75, 100]	[50, 75, 100]
Market	[0.1, 0.2, 0.3, 0.4]	[0.2, 0.3, 0.4]
Employment (persons)	[1000, 2000, 3000, 4000]	[2000, 3000, 4000]
Ecological Integrity	[1, 2, 3, 4] categories of impact	[2, 3, 4] categories of impact
Unintended Environmental Impact	[1, 2, 3, 4] categories of impact	[2, 3, 4] categories of impact

5.4.7 Results

I compare the distribution of results for each weighting scheme with the range of thresholds, to identify which thresholds have a controlling influence on the final result. Results for scenarios with varying preference thresholds are summarised in Table 5.19, and scenarios with varying veto thresholds are summarised in Table 5.20.

Table 5.19 *Matrix showing possible results for each weighting scheme (orange ticked) for preference threshold scenarios, with white crosses indicating a result that did not occur for any threshold values with the specified weighting. Square brackets indicate alternatives are equally ranked.*

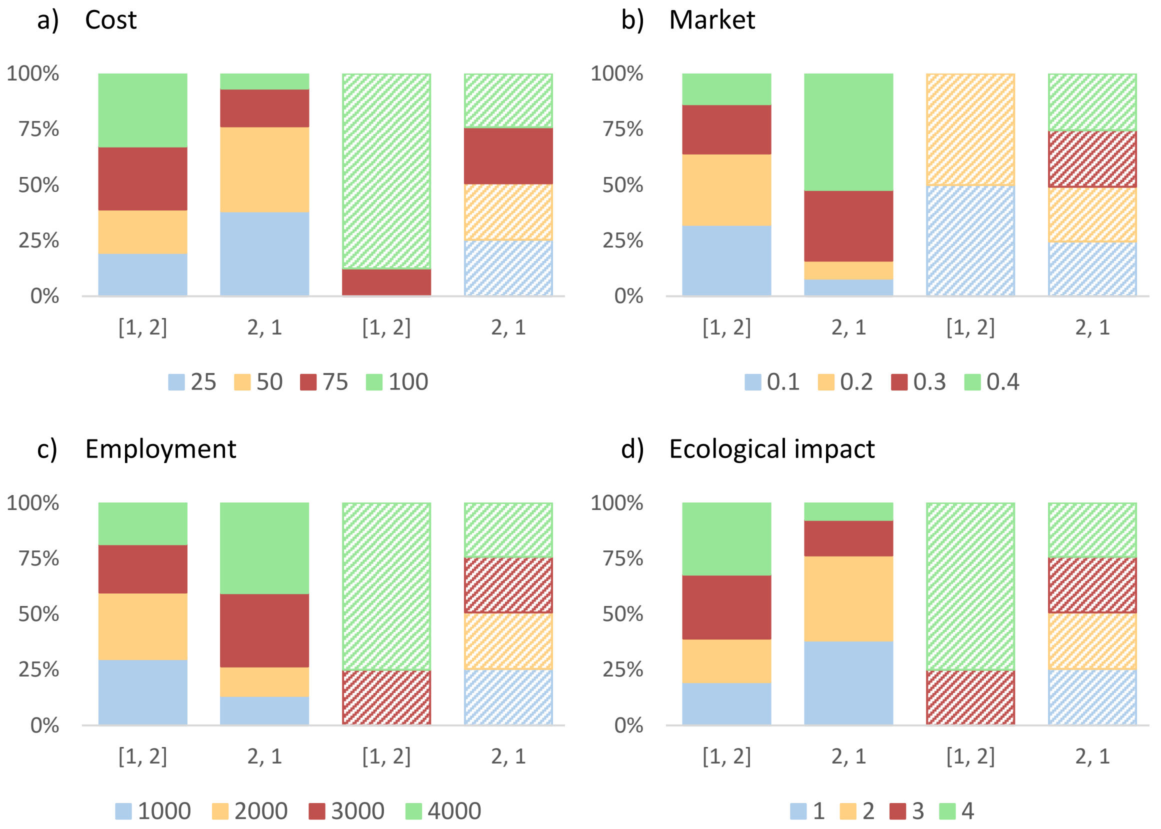
		Employment positive			Employment negative		
Weighting Scheme		Uniform	Econ	Soc/Env	Uniform	Econ	Soc/Env
Possible Alternative Rankings	*[1,2]*	✓	✓	✓	✓	✓	✕
	1, 2	✕	✓	✕	✕	✕	✕
	2, 1	✓	✓	✓	✓	✓	✓

Table 5.20 *Matrix showing possible results for each weighting scheme (green ticked) for veto threshold scenarios, with white crosses indicating a result that did not occur for any threshold values with the specified weighting. Each column represents one set of scenarios. Square brackets indicate alternatives are equally ranked.*

		Employment positive			Employment negative		
Weighting Scheme		Uniform	Econ	Soc/Env	Uniform	Econ	Soc/Env
Possible Alternative Rankings	*[1,2]*	✓	✓	✓	✓	✓	✓
	1, 2	✕	✓	✕	✕	✕	✕
	2, 1	✓	✓	✓	✓	✓	✓

With only preference thresholds, possible rankings for all weight schemes either have both alternatives equivalent, or alternative 2 outranking alternative 1 (Table 5.19). The latter result occurs more commonly with low thresholds for cost, ecological impact and unintended environmental impact, and a high threshold for market (Figure 5.24-Figure 5.26). The impact of employment varies depending on whether it is to be maximised (in which case alternative 2 outranking alternative 1 is more likely at high threshold values) or to be minimised (in which case alternative 2 outranking alternative 1 is more likely at low threshold values).

The only case where alternative 1 outranks alternative 2 is with high weight to economic criteria and employment considered positive (Figure 5.25). Even under these conditions, this ranking requires the highest possible thresholds for cost, ecological impact and unintended environmental impact, and lowest thresholds for market and employment (Figure 5.25). At these values, positive aspects of alternative 1 cause it to outrank alternative 2, but its negative environmental impacts do not impact the decision. However, under other weighting schemes this threshold combination is only sufficient for both alternatives to be considered equivalent (Figure 5.24, Figure 5.26). With high social and environmental weight, and employment aiming to be minimised, there are no threshold values at which both alternatives are ranked equivalent (Figure 5.26), as alternative 1 has inferior performance on all social and environmental criteria.



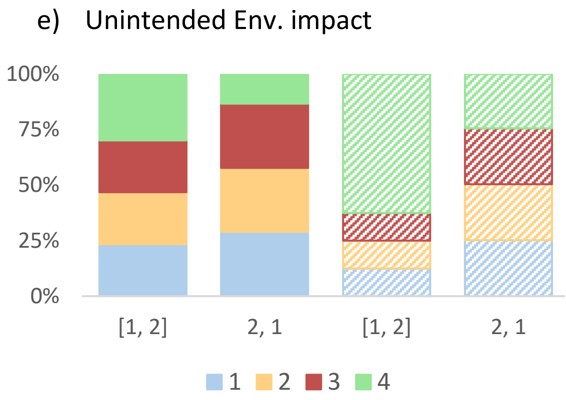


Figure 5.24 *Summary of scenario results with uniform weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios. Hashed bars are simulation results where employment is to be minimised.*

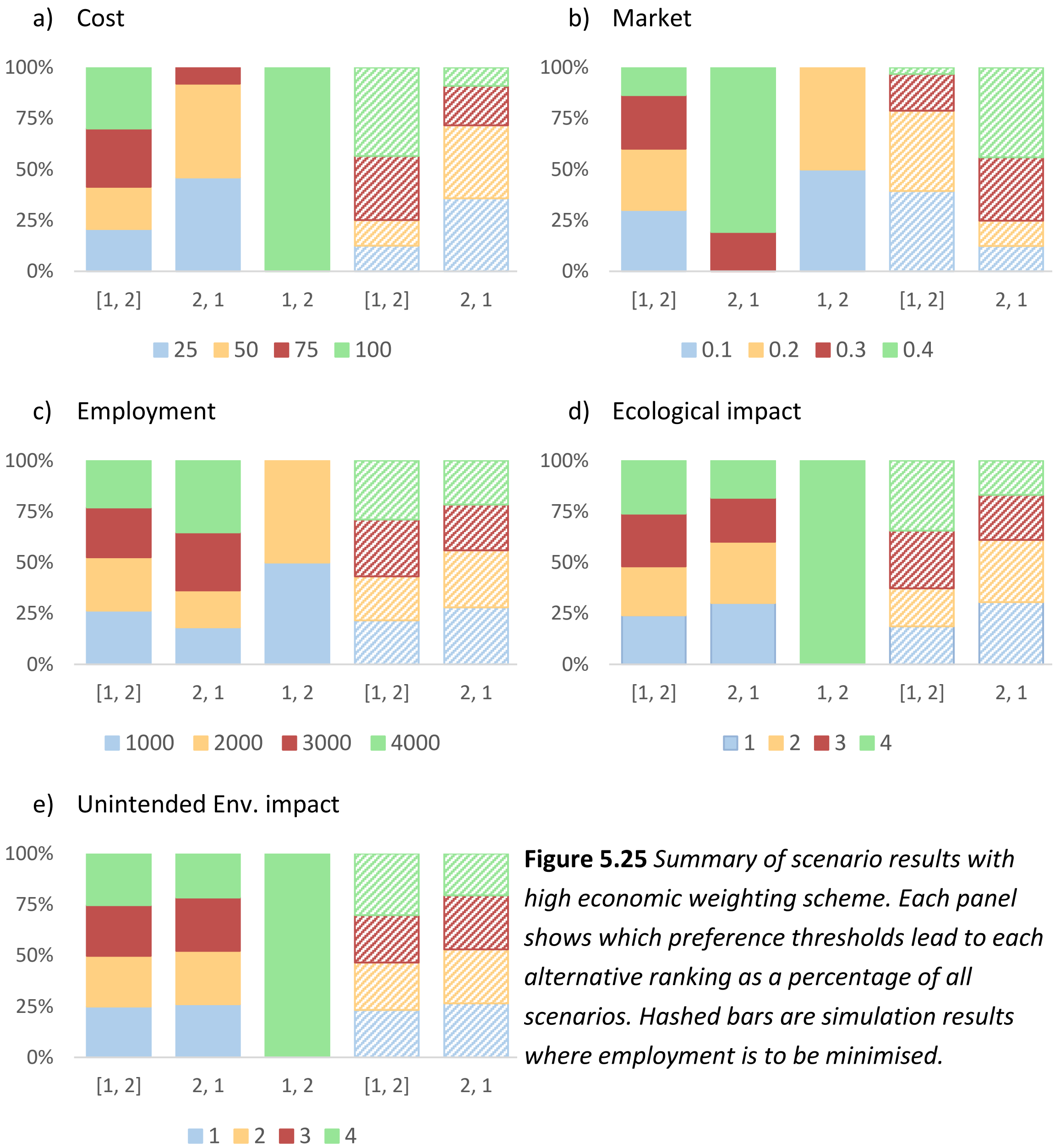
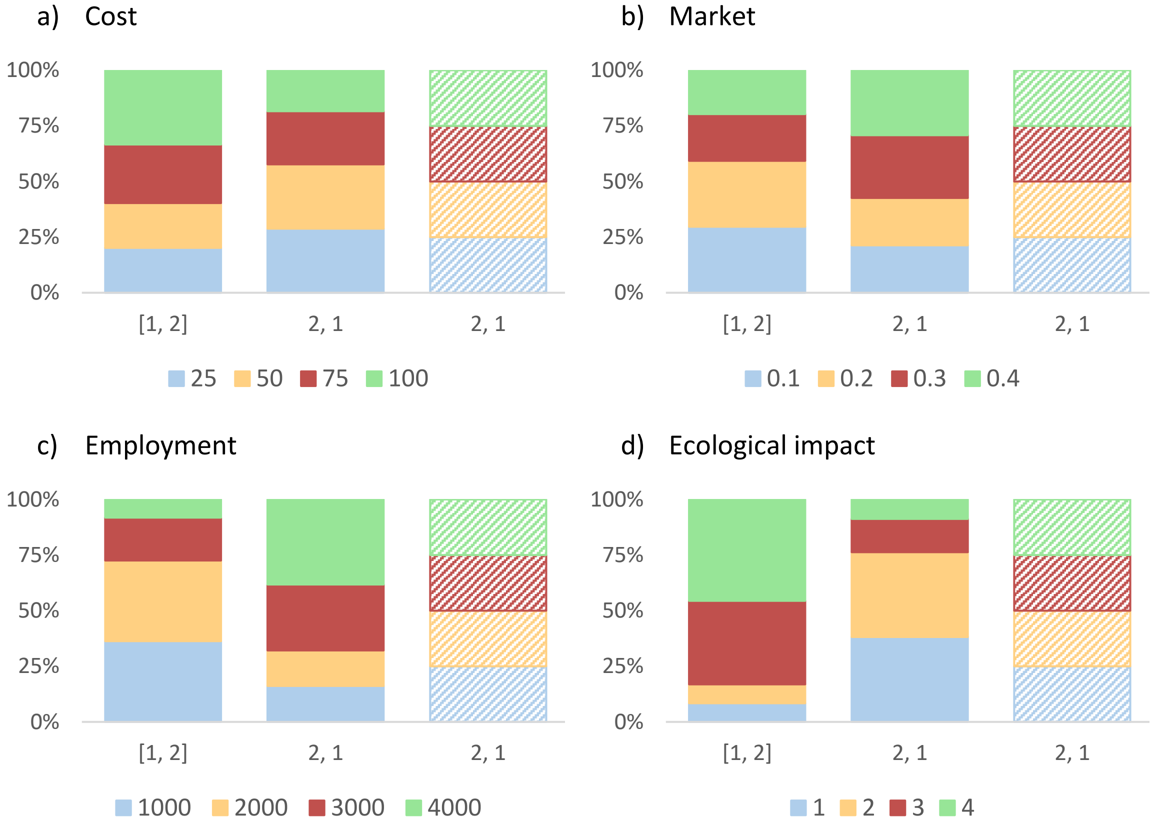


Figure 5.25 *Summary of scenario results with high economic weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios. Hashed bars are simulation results where employment is to be minimised.*



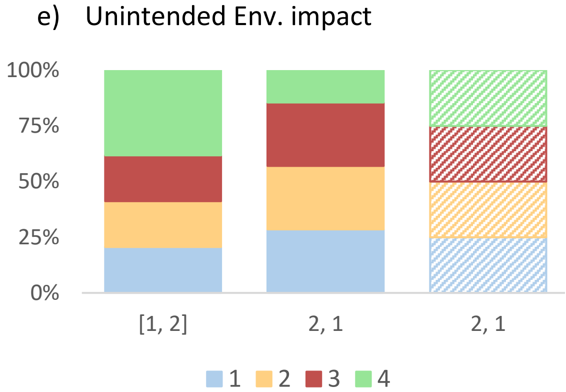
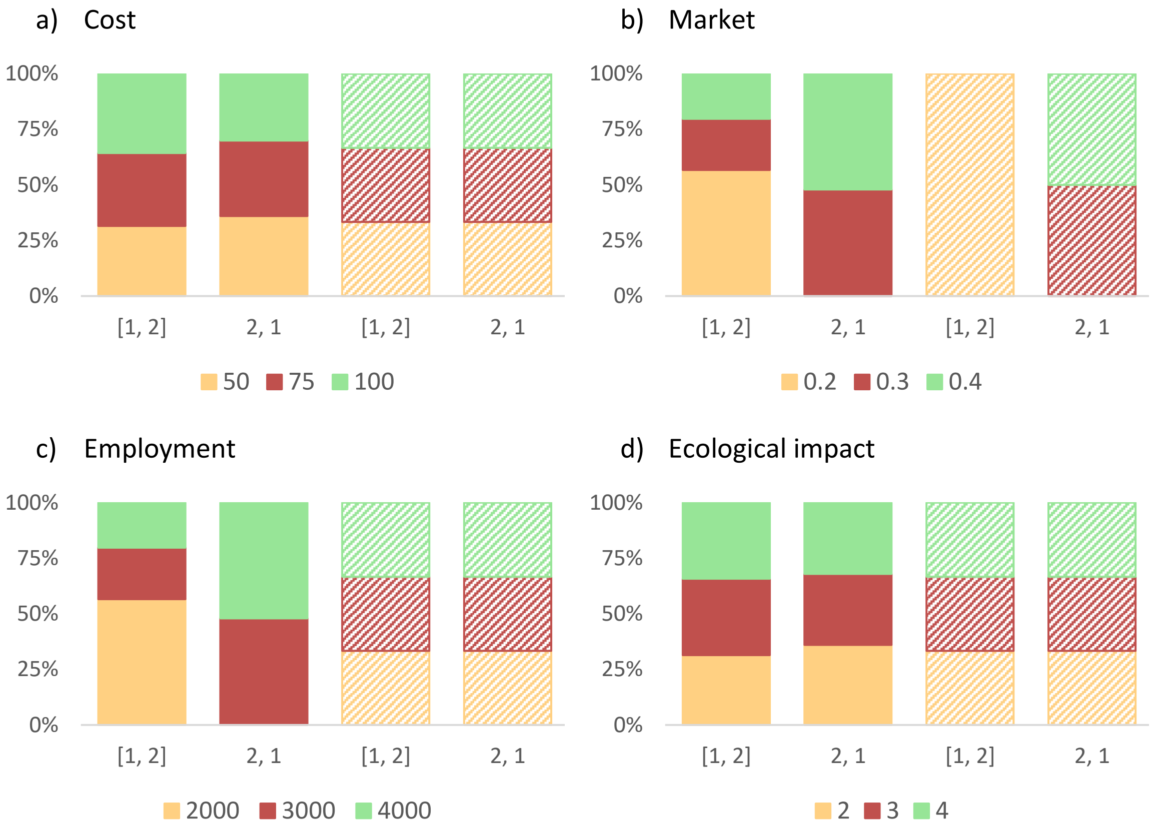


Figure 5.26 *Summary of scenario results with high social/environmental weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios. Hashed bars are simulation results where employment is to be minimised.*

When introducing veto thresholds, the same range of results are possible as with only preference thresholds (Table 5.20) and indifference between alternatives is now possible for the high social/environmental weighting scheme. Veto thresholds on cost, ecological impact and unintended environmental impact do not effect the final result under any weighting scheme (Figure 5.27-Figure 5.29), as these prevent outranking by an alternative that is itself outranked. The additional possible result is caused by a veto threshold of 0.2 on market that prevents alternative 2 outranking alternative 1 overall (Figure 5.29b). A veto threshold on employment also does not impact the result in scenarios where employment is to be minimised (Figure 5.27c, Figure 5.28c, Figure 5.29c). If employment is to be maximised, alternative 2 is prevented from outranking alternative 1 at low veto values. Similarly, alternative 2 also cannot outrank alternative 1 at low veto values for market, but neither threshold changes the range of possible results.



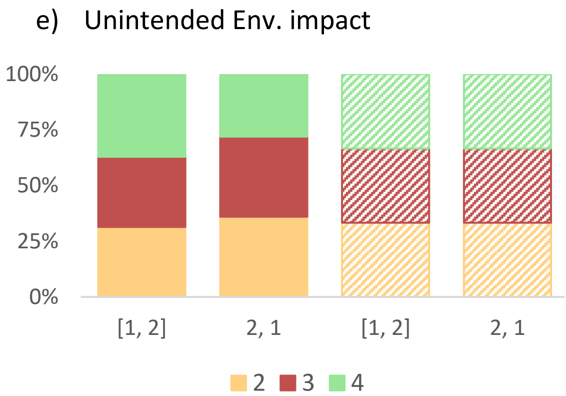


Figure 5.27 *Summary of veto scenario results with uniform weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios. Hashed bars are simulation results where employment is to be minimised.*

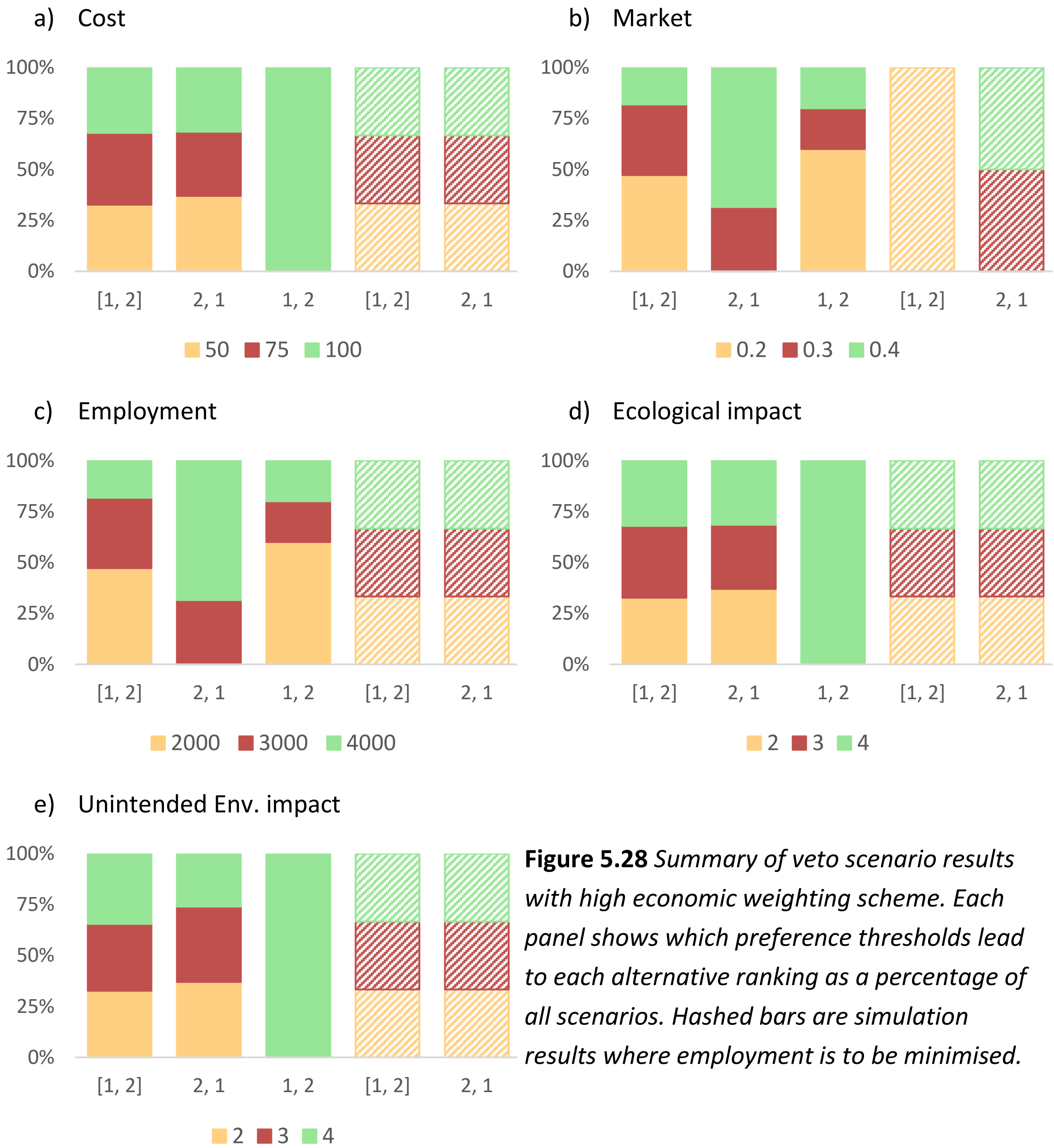
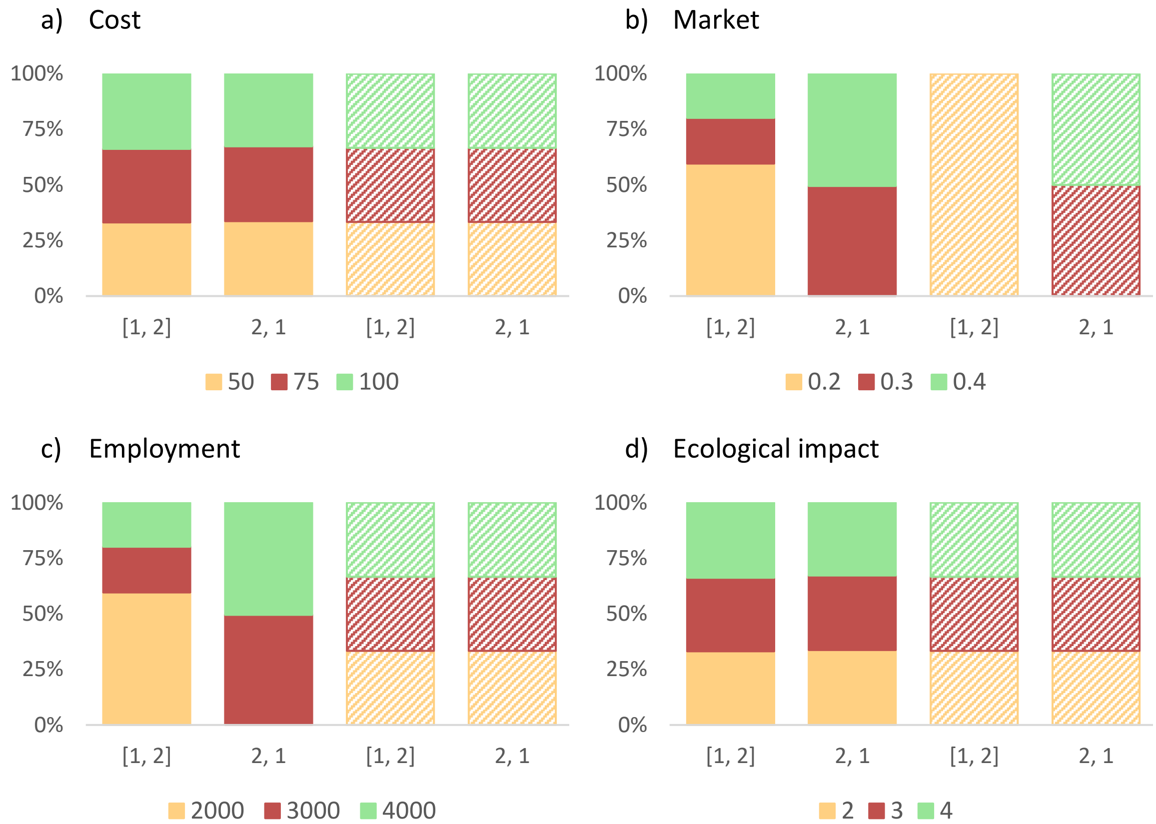


Figure 5.28 *Summary of veto scenario results with high economic weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios. Hashed bars are simulation results where employment is to be minimised.*



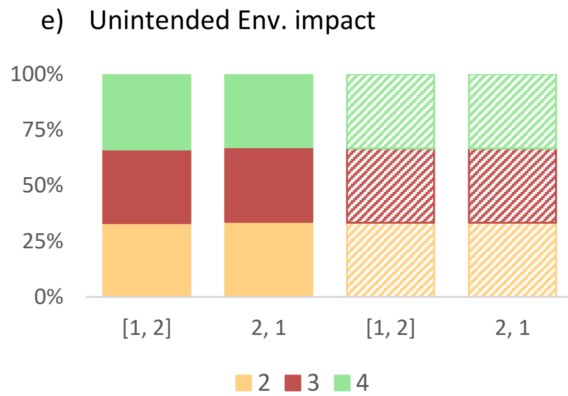


Figure 5.29 *Summary of veto scenario results with high social/environmental weighting scheme. Each panel shows which preference thresholds lead to each alternative ranking as a percentage of all scenarios. Hashed bars are simulation results where employment is to be minimised.*

5.4.8 Discussion

Japan has shown high interest in the potential of its offshore gas hydrate (Konno et al., 2017), and continues to allocate financial and technical resources to gas hydrate development research (Oyama and Masutani, 2017). Environmental concerns could also see natural gas displacing imported coal and oil, as the purity and energy density of methane hydrates would produce fewer emissions, without needing transition to a fully renewable energy system (Zhao et al., 2017); using natural gas to substitute coal and oil in Japanese energy generation and industry has been suggested to reduce CO_2 emissions (Sugiyama and Takeuchi, 2008). As Japan has sought a highly optimised energy system for decades, increased gas usage is one of few possible remaining measures to meet carbon reduction targets outlined from the Kyoto Protocol onwards (Lau et al., 2009). Whether gas hydrate is developed depends on how the initial problem is framed, as policy considerations in Japan may promote gas hydrate development as long as it can be considered not significantly inferior to the current situation. Of the criteria not used, greater measurement of economic impacts would likely strengthen the business case for gas hydrate development over imported natural gas, as domestic production could be taxed, prices could be controlled more readily than for imported gas (hence a positive impact on cost of living) and there may be multiplier effects in the domestic economy from growth in Japanese offshore industry. Infrastructure considerations, such as legislation, are also likely to support gas hydrate development due to energy security concerns.

More comprehensive assessment of LNG import to Japan will likely increase the ecological impact and unintended environmental impacts of this alternative. Similarly, any development will have operational costs that may be relevant in choosing an alternative for long term strategy. As I assume both alternatives use the same import and distribution facilities, only upstream costs are relevant, and these are currently undervalued for alternative 2. The importance of these costs is likely to vary significantly between stakeholders, as the industrial developers would be very concerned if their drilling costs were high, whereas consumers would only be concerned if this cost was passed onto them.

The region discussed here is one section of possible Japanese gas hydrate resources, the focus of previous testing and research. If development here proves successful, and further reserves are established, Japanese gas hydrate commercialisation could be expanded to deposits surrounding the rest of the country (Figure 5.18). If developed widely, Japanese gas hydrate resources may provide sufficient natural gas for Japan to begin export to other gas-poor nations in the region. This broader development for the domestic and export market could be another alternative to consider in a future protocol application. A real-world protocol study at this site could benefit from stakeholder interaction that would generate a greater range of alternatives for comparison, possibly iterating towards an idealised solution.

I have presented weighting for Japan on experience with stakeholders in Alaska, but real weights may differ greatly, as Japanese social and economic norms are very different, and ensure Japan is culturally distinct from any other location studied (Bomhoff and Gu, 2012). Japan also tends to present an outward public narrative of cultural homogeneity that may make representation of a cross-section of society more complicated (Weiner, 2009), as distinct social positions are harder to identify. I have used three different weighting schemes to present a range of inputs, but Japanese priorities may not divide into the same groups seen elsewhere. Future evaluations at this site should include stakeholders throughout the process for accurate and comprehensive criteria weights. As gas hydrate development is being promoted here by governmental and commercial interests, it is important that detailed stakeholder analysis is completed before widespread development proceeds.

One possible impact not presently considered by my protocol is competition between gas hydrate development and other potential economic uses of the site including other energy sources, such as wind farms, or other resource development, such as fishing. Japan has significant offshore wind potential that could be harnessed as a green energy source instead of gas hydrate (Utsunomiya et al., 2015). Which energy is pursued will depend on domestic priorities. Under the Common Rights Fishing System (Li and Xu, 2019), Japanese fishers can prevent activities that impose risks on their fishing activities, which could be used to block gas hydrate development. Most protected fishing areas in Japan are off the northern coast (Matsuda et al., 2016), away from the area of potential gas hydrate development considered here. On the south coast, shrimp are fished in Suruga Bay, and sand eel in Ise and Mikawa Bays (Figure 5.30; Matsuda et al., 2016), but these areas are closer to shore than the gas hydrate deposits, and are also sites for LNG terminals, so are unlikely to be negatively impacted by further development offshore. However, this impact may be significant consideration at some sites, and should be considered an infrastructure criterion.

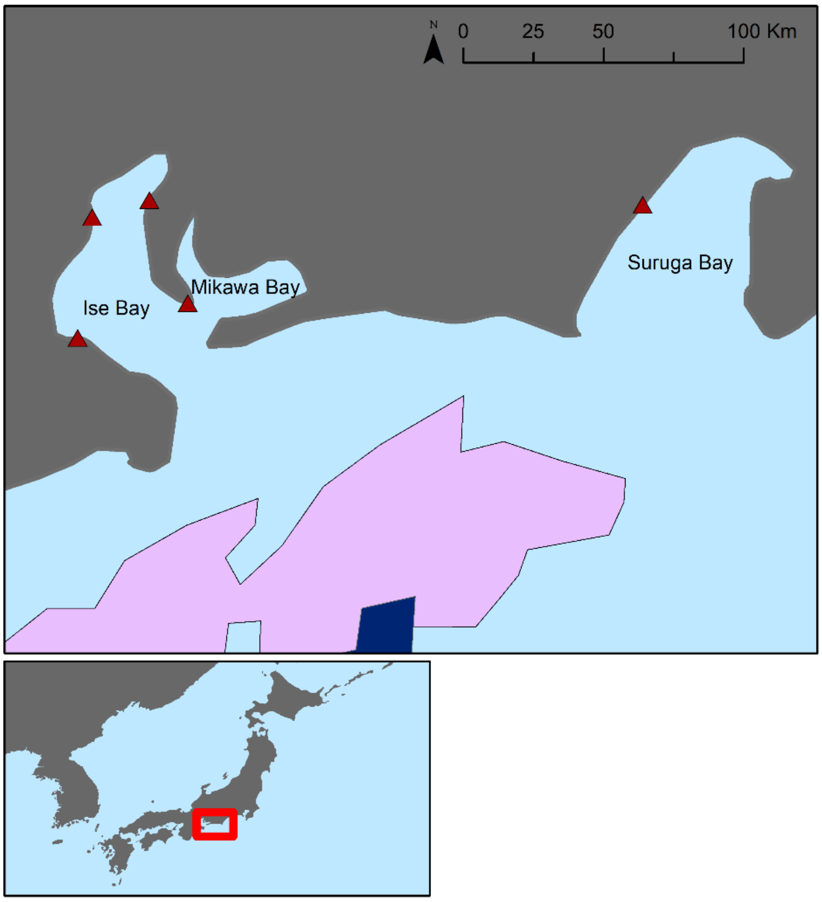


Figure 5.30 *Map showing location of Japanese bays used for fishing with LNG terminals (red triangles) and approximate offshore gas hydrate deposits (pink; MH21, 2010).*

5.4.9 Conclusions

Compared to other sites, gas hydrate development in Japan has been advanced through scientific and commercial testing, including government investment. As such, gas hydrate development may not need to outrank other alternatives to be considered viable for commercialisation here. This location presents one example of how to frame the problem and measure criteria impact when considering an offshore site.

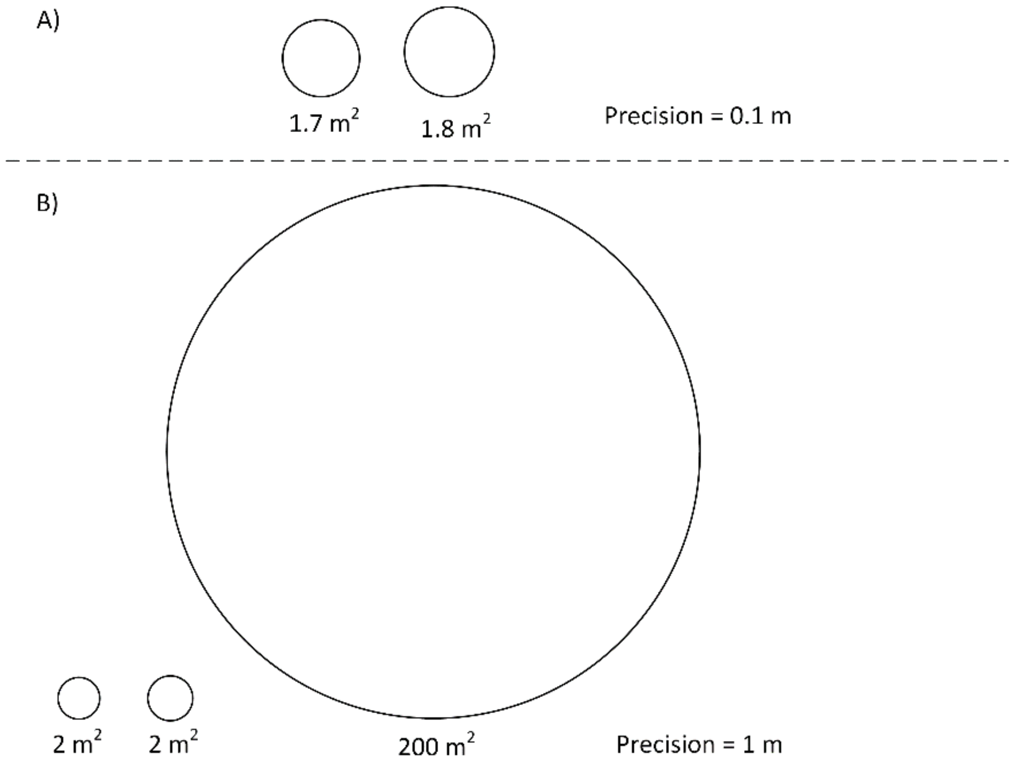
This example case study has the smallest range of alternatives and criteria of any I have completed, leading to a limited range of possible rankings. The results here suggest this example was near to the low limit of dimensions needed to define a problem, as most results are possible under most weight combinations.

5.5 Discussion

There are certain points to highlight within these cases that suggest possible protocol refinements, or considerations when using the protocol or interpreting its results. I discuss these findings across sites to explore the capabilities and caveats of my created tool.

The Japan case highlights a potential issue as it is difficult to attribute impact to a single end user, if the alternative under consideration supplies additional markets (Vallero, 2019), such as the overseas projects that supply Japan amongst multiple locations (Lochner and Bothe, 2009). For more accurate measurement, attempts can be made to deconstruct a large commercial operation through life cycle assessment (Hellweg and Canals, 2014), or impact can be assigned proportionally to the amount of total produced gas that is used by the market under consideration (Suh and Huppes, 2005).

Another protocol issue, shown in the Canadian case, arises when comparing alternatives that are drastically different in scale. The ability to compare between two similar scale alternatives may be lost during comparison with another alternative that is much larger in scale, as impact estimates for the larger alternative may have error margins that provide indifference thresholds larger than the difference in performance between the remaining alternatives (Figure 5.31). Taking one criterion in the Canadian case, the cost error margin for alternative 2 is $18 million, significantly below the error margin of $500 million that was used as the indifference margin during scenario analysis, as the error margin for alternative 1 (Table 5.21). Therefore, if only comparing alternatives 2 and 3, preference thresholds can be expressed that are above the new error/indifference margin, but below the difference in impact between alternatives, which was not possible with the previous indifference thresholds. As a result, the final alternative ranking does not remain independent to irrelevant alternatives (preferences between two alternatives change with the inclusion of a third alternative), a known ELECTRE limitation with poor quality data (Figueira and Roy, 2009). In future applications, if data precision is insufficient to differentiate all alternatives, it may be necessary to conduct separate comparisons, or omit criteria with imprecise data. Alternatively, ELECTRE thresholds can be varied using a linear function, which is more complex to define than a single value, but would enable all comparisons to occur within a single study (Rogers and Bruen, 1998).



A) With two areas measured to the nearest 0.1 m, it is clear which is smaller. B) Adding another area that is significantly larger reduces measurement precision to 1 m, meaning it is no longer possible to state which of the first two areas is smaller.

Figure 5.31 *Simplified explanation of how measurement precision, which controls indifference thresholds, can lead to failure for the protocol to adhere to independence of irrelevant alternatives.*

Significant gas hydrate deposits are found offshore (Boswell and Collett, 2011), an area of potential development considered in my Japan case study. The protocol is designed for either onshore or offshore projects, so no protocol adjustments are necessary when evaluating offshore development, and offshore projects should consider the same suite of criteria as onshore projects (Figure 4.2). Certain criteria unused in the Japan case, such as subsistence, are omitted due to specifics of this site, but will be relevant at other offshore sites, and even within Japan’s EEZ there is potential competition from domestic fishing, although this is a commercial enterprise rather than motivated by subsistence needs. Although not the primary area considered in my Canada case study, offshore gas hydrate deposits at the Mackenzie Delta coincide with marine mammal calving grounds used for hunting by the local indigenous population, indicating how this criterion could be relevant in an offshore setting (Osadetz and Chen, 2010; Waugh et al., 2018). Other unused criteria (e.g. taxation, legislation) could be valid considerations for Japan and other offshore sites, and were only omitted here due to practical limitations on time and research resources available to complete the protocol in this case. Criteria assessing impact on humans, such as health, can be evaluated in offshore assessment by considering the employee population, or the domestic market where gas is sold. When choosing criteria in any problem, it should be understood what impacts are being omitted, and how this is likely to affect the final result. Ideally, in commercial cases, all significant considerations in project design should be included in evaluation. External criteria validation before building an impact matrix, suggested for future protocol applications, ensures that all impacts relevant to stakeholders are measured.

Table 5.21 *Comparison of cost indifference margins if using two or three alternatives for the Canadian case study.*

	Alt 1. Mackenzie Valley pipeline	Alt 2. Supply to Tuktoyaktuk	Alt 3. No hydrate development	**Indifference**
Cost ($CAN million)	10500	88	0	**500**
Cost ($CAN million)	*Omitted*	88	0	**12**

I have less frequently evaluated criteria that I classified as infrastructure criteria (Figure 4.2) than my other criteria groups but, in some cases, they may provide the main discrimination between alternatives. Legislation (I1) and lifespan (I2) are included in the Russia case, and could be measured similarly elsewhere where relevant. Technology (I3) becomes a significant consideration if comparing different production methods, a question that may arise further into the gas hydrate development lifecycle (Marcelle-De Silva and Dawe, 2011). For any case study, logistics (I4) and resource distribution (I5) vary between alternatives when considering export or domestic markets, and either could be the focus of a given case. Therefore, my limited use of infrastructure criteria largely results from my definition of each problem, and these criteria are appropriate for future evaluation of these, and other, sites. Since I have not used these criteria with external stakeholders, field studies are required to understand their importance in real-world decision making, and the range of decision weights allocated to these criteria by different stakeholders.

Some typical criteria utilise assessment approaches that provide commonly understood units of measurement, such as monetary quantification of economic criteria. For less familiar criteria I have used varying valuation approaches, seeking the best way to measure each impact. The protocol design allows this flexibility in assessment approach, as each impact can retain its natural scale throughout evaluation. Certain valuation approaches work for scenario analysis, but may be less effective in real-world applications, as values with unfamiliar units are difficult for stakeholders to contextualise (such as the REES index in the Japanese case). If stakeholders cannot interpret the scale they will be unable to provide meaningful threshold values. Depending on the precise protocol application, it may be beneficial to sacrifice quantification accuracy to use qualitative assessment that improves stakeholder accessibility, if this approach greatly increases the number and diversity of stakeholders able to contribute. With qualitative criteria, assessment precision is reflected in the number of impact categories. In Russia and Canada I used 7 and 8 point Likert-style scales (Allen and Seamen, 2007), whereas qualitative assessments for Japan used 4 categories in risk matrices (van Lenteren and Loomans, 2006), so there were fewer possible values for decision thresholds. Using more categories enables a greater range of threshold values, but the approach must remain reasonable, with clear, distinct definitions for each scale point.

One of my reasons for choosing ELECTRE was its non-compensatory behaviour, aligning with strong sustainability, achieved through the use of veto thresholds (Figueira et al., 2013). In fact, veto thresholds show my protocol's nuanced representation of strong and weak sustainability simultaneously, as damage to natural or human capital below the veto threshold is tolerable (weak sustainability), but damage above the veto threshold that may remove vital functionality is not (strong sustainability; Neumayer, 2003). Veto thresholds limit compensatory behaviour, setting maximum limits on negative impacts, irrespective of the resultant positive impacts, even if the criterion in question is given low weight. A criterion simultaneously given low weight and a low veto threshold that affects the final result should be discussed with the stakeholder concerned, as it suggest the criterion is more valuable than it has been weighted, or the threshold defined is unnecessarily narrow. There is a feasible explanation for this discrepancy however, with criteria not thought to be impacted by current proposals (low weight), but significant if impact occurs (low threshold). In my case studies, vetoes often favour smaller scale alternatives, as any negative impact is sufficient to prevent outranking. As such, veto behaviour encourages a cautious approach to industrial development, where social and environmental assets are not sacrificed for economic returns. Vetoes are not purely designed to restrict development however, and economic or resource vetoes can recommend against industrial development if production targets are not met, so ensure benefit is commensurate for the scale of impact. Introducing veto thresholds changes the possible results in each case, and leads to fewer scenarios where two or three alternatives are ranked equally in Canada and Russia. Although project design is more complex as a result of veto behaviour, considering all impacts initially will likely reduce opposition during public consultation.

In all cases there are scenario results where multiple alternatives are ranked equally, which provides limited value to the decision maker, as it suggests further considerations are necessary before recommending an alternative. Future analyses that better constrain impact estimates with reduced error margins will make it less likely alternatives will be ranked as equivalent. In some locations, such as Japan, it may be sufficient that gas hydrate development is as-good-as the current resource supply, if gas hydrate development is generally supported, so an indifferent ranking may be adequate for development to proceed.

5.6 Conclusion

These three test cases present the range of problems I anticipate the protocol being used for in future fieldwork. A number of different alternative ranks result in each case, suggesting my protocol can be applied to comparisons in the early development phase of gas hydrate commercialisation where data is imprecise. The criteria set defined by my protocol provides a range of possible considerations for multi-dimensional analyses of gas hydrate commercialisation in both onshore and offshore settings, the two main environments where gas hydrate is found. Care should be taken when defining alternatives and choosing assessment criteria to ensure a fair and balanced assessment, ideally with external input from varied stakeholders. Veto thresholds introduce caution into project design, incorporating strong sustainability into project assessment, although using these thresholds may have a tendency to recommend small scales of development as a result. These examples provide frameworks and suggestions for future studies, as well as showing the possible versatility of the designed protocol. Future analysis should include stakeholder input, as well as more accurately defined impact dimensions and alternative solutions for thorough assessment.

Chapter 6 Summary, Final Protocol and Suggested Future Work

6.1 Summary

This work provides the first structured analysis of the social, economic and environmental impacts of gas hydrate commercialisation. Although gas hydrate is increasingly being considered as an unconventional source of natural gas, assessment considering the broad implications of production has so far been lacking. As a result, there is no clear approach for establishing the viability of any gas hydrate development proposal, even at sites where production has been considered technically. This thesis aimed to devise and test an assessment protocol that fulfilled this need.

Chapter 1 introduced gas hydrate as a resource, while **Chapter 2** explored the evaluation techniques previously used in similar projects, summarising the differences between MCDA and CBA, and the strengths and weaknesses of different MCDA methods. **Chapter 2** also provided a structural basis for my protocol by reviewing impacts considered in other resource assessments. Finally, **Chapter 2** explained my chosen MCDA technique, ELECTRE III, used because of its non-compensatory behaviour provided by veto thresholds, and its ability to accommodate imprecise qualitative and quantitative data with varied measurement scales in a single study.

To create production estimates that fit my requirements, **Chapter 3** used numerical modelling to explore the impacts of gas hydrate saturation heterogeneities on gas production under commercial depressurisation, using a 2D model of the Alaska Mt Elbert site, and a range of different gas hydrate distributions. I found that overall mean gas hydrate saturation had a first order control on gas production, but local heterogeneities, and areas without gas hydrate in particular, caused fluctuations in gas flow through the formation and production rate at the well. I also found that gas production in such high permeability systems was primarily controlled by local variations at the production front. Overall, this modelling generated a usable error margin for gas production estimates.

In **Chapter 4** I created a new MCDA assessment protocol using quantitative and qualitative assessment of economic, social, environmental and infrastructure impacts of commercial gas hydrate development, including the production modelling from **Chapter 3**. This protocol structures assessment through an impact matrix. The impact matrix is discussed with stakeholders to understand which impacts they prioritise in decision making, leading to a calculated rank order of development alternatives. For testing, I collected primary data through interviewing stakeholders connected to gas hydrate development in Alaska, as described in **Chapter 4**. My protocol results identified a division between two opposing stakeholder positions depending on which criteria they prioritised, with one group primarily prioritising economic criteria and the other group assigning most decision weight to social and environmental criteria. The viability of commercial alternatives varied between stakeholders, although gas hydrate development was universally evaluated as unlikely under present day conditions. Practical considerations during fieldwork suggested that earlier stakeholder buy-in, more decision support for assigning thresholds and incorporation of traditional knowledge could all improve the protocol in future applications.

To further describe the range of possible scenarios where use of this protocol may be appropriate I presented possible gas hydrate projects at three other sites, the Mackenzie Delta in northwest Canada, the Messoyakha field in central Russia and offshore southern Japan, with these described in **Chapter 5**. For each site I used secondary data to define possible development alternatives, then calculated the rankings resulting from a range of hypothetical weights and decision thresholds. Overall these case studies give a general indication of how to approach the problem in different settings, and the style of alternatives that are appropriate to consider. Operational issues highlighted across these case studies are also discussed in **Chapter 5**, leading to the final protocol recommendations given below.

6.2 Final Protocol

The primary aim of this thesis was to create, test and refine the first comprehensive assessment tool for evaluating gas hydrate development proposals. I now present the final form of the protocol (Figure 6.1), building upon the description in Section 4.3, and refinements discussed in Sections 4.6 and 5.4.8. Primary considerations at each of the eight protocol stages are described below. The protocol is designed to be a participatory decision-making process throughout. External input should be sought where appropriate from stakeholders and subject experts, and the following stages should be considered iterative, with each protocol element refined through multiple rounds of consultation. Sourcing stakeholder input early and often increases process transparency and facilitates greater buy-in, which creates an overall more positive experience for all parties involved.

1. Identify and define the problem and the main goals and objectives.

    i. At this initial stage, the problem setting and primary aim need to be determined. It is likely that the problem will be presented by the decision maker, but the facilitator needs to ensure there are clear goals to identify a successful protocol outcome.

    ii. The primary question under investigation needs to be clearly specified. For example, in some cases it will be sufficient that gas hydrate is not inferior to other alternatives (my Japanese case), while in other cases gas hydrate commercialisation will need to outrank other alternatives to be pursued.

    iii. Using facilitators with connections to an area simplifies developing stakeholder connections, but the facilitator must remain unbiased throughout, which can be easier from an external viewpoint. Otherwise, facilitators need to be numerate and adept at summarising and communicating information, but do not need a specialisation in any of the areas assessed through the protocol.

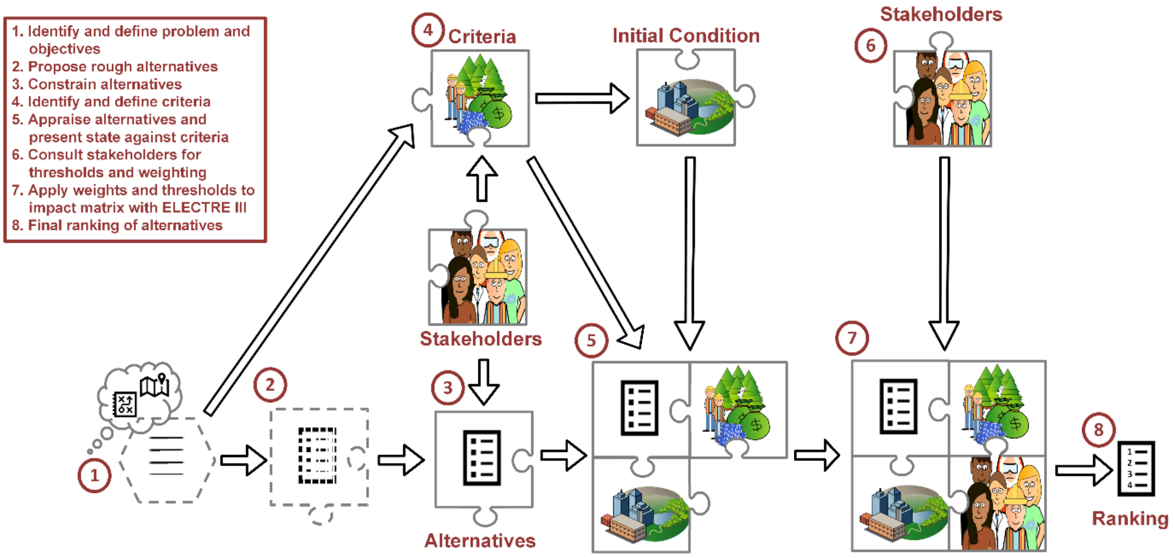


Figure 6.1 *Final protocol workflow*

2. Propose roughly defined alternatives to structure the problem.

    i. Each alternative is a possible solution to the defined problem, with enough variation between alternatives that they can be differentiated during evaluation.

    ii. Although the protocol can be executed with as few as two alternatives, results are more nuanced when comparing more alternatives. Comparing more alternatives requires more resources, so research and time available constrain the upper limit on number of alternatives.

iii. Alternatives can be compared directly if their impacts are similar in scale, but variable thresholds or very well constrained data are necessary if comparing alternatives whose impacts vary over orders of magnitude.

iv. Not developing gas hydrate is a valid alternative to consider in many protocol applications. This alternative provides a level that gas hydrate development must outrank, or not be outranked by, to be a viable commercial venture.

3. With external input, constrain specific alternatives which meet this problem.

   i. Discussing alternatives with stakeholders ensures their interests are met, and the alternatives are appropriate to the site. Each alternative should be defined through multiple aspects of measurable performance.

   ii. Alternatives should be presented as simply as possible while still conveying all relevant information, to enable stakeholders with varying backgrounds to participate equally.

   iii. Alternatives should be defined over the full supply chain from resource production to end user. All alternatives within one study should have the same scope, measuring comparable impact with the same considerations for each alternative, which may require deconstructing impact from an existing project to compare projects equally.

   iv. Stakeholders may present new alternatives during consultation. If they provide a viable new solution that is validated by other stakeholders, the new alternative will need to be explored and its impacts defined.

4. Incorporating stakeholder input, select criteria that evaluate how well the proposed alternatives succeed against the defined goals.

   i. Criteria need to measure success of any alternative in meeting the assessment goals, and capture impacts relevant to stakeholders (Figure 6.1).

   ii. I have identified five criteria areas (resource information, economic criteria, social criteria, environmental criteria, infrastructure criteria) under which impact can be defined through a series of sub-criteria (Figure 4.2). Evaluations need not use criteria from all five areas, although this approach helps to balance assessment, and omitting one dimension of impact should be justified and clearly considered in any results. It is not necessary or advisable to use all sub-criteria in every evaluation. Efforts should be made to create a balanced assessment that does not fundamentally favour any alternative through criteria choice.

iii. Assessment should avoid measuring the same impact through multiple criteria, as this approach introduces double counting that is likely to influence the final protocol result.

iv. Any evaluation should also consider what is excluded through choice of criteria, if any omitted criteria are important to stakeholders, and whether these criteria would alter the final result if included.

5. Appraise how all alternatives would impact the initial condition of the site using the evaluation criteria in an impact matrix.

i. My protocol can include qualitative or quantitative criteria, or both simultaneously, as there is no requirement to standardise units across criteria. Quantitative criteria are preferred by some stakeholders, who consider quantification a more robust approach, so may be necessary for certain audiences. Qualitative criteria can include impacts that are not readily translated to a numerical scale, and may also facilitate stakeholder input above quantification with unconventional units.

ii. I have used varying approaches for measuring criteria to test protocol versatility, and make best use of the limited data available. With imprecise data, qualitative approaches often proved more successful at assigning an impact, as these have an inbuilt uncertainty when compared to precise quantification. Quantification may also omit dimensions of a complex impact that is difficult to assign a single value, such as impact on cultural assets. When using qualitative criteria, the number of categories dictates the range of possible threshold values.

iii. Impact assessment should have consistent methodology between alternatives, as an incomplete assessment may under- or over-state the impact of any alternative. Impact is not limited to point of production, and the full supply and distribution chains should be considered where relevant.

iv. Traditional knowledge should be incorporated where appropriate, to accurately measure impact, and make use of the best data available. More broadly, efforts should be made to accommodate indigenous stakeholders, and achieve their buy-in to the process.

v. The limit of each impact estimate should be clearly considered and stated alongside impact measurements. Limits are especially necessary when analysing one component of a broader system, such as the incremental impact of gas-hydrate-sourced gas being transmitted through an existing pipeline network.

vi. Criteria may have to be omitted if there is insufficient data to generate reasonable impact estimates. Limited data availability reduces the ability of the protocol to differentiate between alternatives, but data quality should improve as commercialisation becomes closer to reality.

6. Consult the stakeholder groups involved with the problem for criteria weights and thresholds.

   i. I have identified six stakeholder groups (government, industry, local communities, indigenous communities, environmental organisations, scientific community) that are found at most sites. Multiple representatives should be consulted for each stakeholder group, as opinions vary within these groups. As found in Alaska, priorities may overlap between groups, which can identify societal divisions to consider in any proposal.

   ii. All reasonable efforts should be made to represent all stakeholder groups present. The facilitator is responsible for ensuring assessment is equally accessible to all parties. Participation requires commitment from stakeholders, who must provide free, prior and informed consent and receive value commensurate to their input.

   iii. For offshore development, stakeholders can also be surveyed onshore where the produced gas would be used, or where production infrastructure and labour originate.

   iv. Each stakeholder provides a set of criteria weights based upon their priorities. Weights can be elucidated using the revised Simos' procedure, which has proven simple to understand and quick to complete with a range of stakeholders.

   v. Stakeholders should also understand and provide preference and veto thresholds. Preference thresholds establish what level of impact is necessary to differentiate alternatives. Veto thresholds prevent outranking if there is any aspect of alternative performance that is insufficient for an alternative to be allowable. Veto thresholds promote a cautious approach to development as a result, favouring smaller scale alternatives that have less impact across all criteria. Stakeholders must understand that thresholds measure the difference in performance between alternatives, and not aspirational levels of performance for any alternative to exceed or remain below.

vi. Decision support can increase stakeholders' ability to provide usable thresholds, including contextualising the problem by constraining possible threshold values or translating stakeholders' qualitative statements to thresholds, as long as the facilitator does not unduly influence this process. Stakeholder input may also be limited to criteria they are experienced with, to build a cumulative threshold set between multiple stakeholders.

vii. Stakeholders can omit individual thresholds if they are unable to provide reasonable values; the protocol can compute results from a partial threshold set, although too many omissions may invalidate the process.

7. Use stakeholder input to weight criteria and process alternatives with ELECTRE III.

    i. Logical consistency checks can be used between thresholds and weights, as high weight criteria are expected to have narrow preference thresholds. Logical inconsistencies should be followed up with stakeholders to provide justification or adjustments.

    ii. Indifference thresholds originate from the error margin on each impact, and so should not be sourced from stakeholders. Stakeholders' preference thresholds may be below data indifference thresholds, at which point the indifference and preference thresholds are set equal for computation, and the data quality is investigated as potentially insufficient for the problem.

    iii. In addition to weights and thresholds, stakeholders should also be asked for their presumed alternative ranking to benchmark the protocol results. Significant differences between stated and calculated rankings may indicate that an important factor is not captured by the protocol, or that there is a misconception amongst stakeholders.

iv. Hypothetical weights can be used to identify the range of possible solutions, but this approach is not suitable to answer which development alternative is most appropriate to those impacted.

8. Establish a ranking order of suitability.

i. The final protocol output is a series of possible alternative rankings, with one ranking for each stakeholder who provided weights and thresholds, although different sets of thresholds and weight values may lead to the same ranking.

ii. Stakeholder weights alone are a useful output that identifies societal divisions and common interests between stakeholders from different backgrounds.

iii. Sensitivity analysis should be conducted by varying weights or criteria to test the stability of concluded rankings.

iv. The protocol is designed as a decision aid that structures information for a decision maker, but the results should be considered in the context of the decision, and say nothing about the viability of any alternative not considered. Weights are also situation dependent, so should not be transferred between sites in applications where the best ranked alternative will proceed commercially. Stakeholder support or opposition for specific projects cannot be inferred from data collected at a different site.

6.3 Limitations

As gas hydrate has yet to be developed beyond preliminary scientific and technological testing (Li et al., 2016), available information was limited at each site considered. Data quality will improve through additional studies as commercialisation becomes more realistic, especially if impact assessment is made a regulatory requirement. Therefore future studies may be able to more accurately portray and compare realistic development scenarios. The Russian and Japanese cases were complicated here by limited availability of English language data, which would not hinder future assessments by those fluent in the language. Lack of current commercial gas hydrate production also raises the possibility of additional impacts that I have not considered or been able to predict, although any additional impacts should fit within the hierarchical structure I have defined. My numerical modelling identified how relatively small heterogeneity in one parameter used to define subsurface gas hydrate reservoirs can have significant impact on ultimate gas production. Other parameters not tested, such as heterogeneous permeability distributions, could have similar impacts that may cause further variation in gas production estimates, although the results I computed are appropriately accurate for use in this work where many of the criteria values remain uncertain.

Limitations on time and resources made it impossible to apply the protocol collaboratively as designed in each location. In Alaska, developing a stakeholder network required extensive investigation of previous public consultations and gas hydrate test projects, followed by frequent email and telephone exchanges to build a relationship over many months, an approach too time consuming to repeat at any other site. As such, I am unable to provide conclusions on the real-world acceptability of my other development proposals, although the primary aim of these case studies was testing protocol flexibility, not making policy suggestions for any location. Even with the Alaska case, my fieldwork primarily aimed to test the protocol and investigate stakeholder opinions towards gas hydrate production generally, not to recommend a specific development style as a future course of action. Without stakeholders, I do not have specific weighting and threshold values in each case study, and instead I use hypothetical weights based upon my Alaska fieldwork. This approach assumes Alaskan stakeholders opinions hold globally, which is highly unlikely, as each location considered has a distinct natural and human environment. The Mackenzie Delta has many geographical and social similarities to Alaska, but lacks a history of resource development that was an obvious influence on all Alaskan stakeholders (Ashford et al., 2012a). Russia and Japan have very different social structures, and different governmental systems, that developed over centuries (Bomhoff and Gu, 2012; Yakovleva, 2011), and stakeholder priorities will vary accordingly. Although my hypothetical weights may not represent known stakeholder views towards specific projects, they provide a range sufficient to explore potential outcomes in each case. However, new stakeholder viewpoints could exist that create alternative rankings not presented in my scenario results, especially if stakeholders equally prioritise criteria that were on opposite sides of the debate in Alaska, such as economic and environmental impact. In the event of gas hydrate commercialisation, actively seeking stakeholder participation is essential for a representative assessment with accurate weights.

One limitation of this work is that, while a method was chosen to explicitly avoid trade-offs as these were not wholly appropriate in the problem under consideration in my opinion, many stakeholders naturally approached the decision using trade-offs. While this behaviour can be accommodated within ELECTRE, it is used explicitly within some other methods. Therefore my method potentially did not best represent the true preference elucidation process of some stakeholders. However I also believe this thought process should be challenged, and some stakeholders did appreciate the opportunity to provide limits on compensation. I learnt social science research methods as this project progressed, and would likely approach the problem differently now based upon the experience I developed through research and in the field. I remain happy with my choice of ELECTRE despite its complexity as many of the capabilities I identified as useful, such as the easy incorporation of uncertain data or veto thresholds, were valuable.

A known limitation throughout this work is the relatively limited amount of fieldwork. Any study hoping to represent the views of a society on an issue needs thorough integration within that society to achieve its goals. While the study in Alaska was successful in approaching and representing a range of stakeholders, it was by no means comprehensive. Personal health issues and the sheer distance between my origin and my field location limited the opportunity for further study, but it would be improved by more work alongside my Alaskan contributors in understanding perspectives that were only briefly touched here. There was a level of distrust from some stakeholders that was difficult to overcome in the time available. Stakeholders were also justified in choosing not to participate if they saw limited return as I was not in a position to influence future policy at the region.

While my study attempted to find the most generally acceptable solution, it did not consider possible conflict and consequences when attempting to action that solution. It also assumes a logical and rational unbiased decision maker, as there is nothing ensuring the recommended course of action is chosen. It would be an interesting exercise to feed the results from this work back to the original participants and then explore how they would respond with knowledge about the preferences of all other stakeholders, and what collaboration and competition would develop.

Outside Alaska, the cases presented here were devised and defined by me, without the external input that I identify as crucial for a successful application of the protocol. Therefore, while the studies on Canada, Russia and Japan were informative of the adaptability of the protocol, the results cannot be used to infer policy direction in any location. The solutions are heavily dependent on the problem context I have defined and a solution performing well here does not necessarily make it more viable in reality. Therefore the utility of these results is limited beyond prompting future investigation, and showcasing the style of problem this protocol was devised for.

The model I have built here is not fully dynamic as the problem structure is defined relatively early and then not adjusted in terms of redefining alternatives or adding or removing criteria unless there is a gap considered essential to fill. A more dynamic model that allows further customisation within the process could be more useful in some scenarios where the problem is poorly defined to begin. As a result it would often be useful to conduct appraisals iteratively, building upon previous results, and my work here provides the foundation for possible future study, or comparison with other MCDA methods.

6.4 Future Work

My numerical modelling concentrated on heterogeneities in hydrate saturation, which had significant impact on the gas production profile. There are many other modelling refinements that could be applied to better represent complex natural systems and inform future commercialisation, providing an indifference threshold for protocol applications. Heterogeneity in parameters such as porosity and permeability will also affect the gas hydrate distribution, and may accordingly impact production. The response of my modelled system to heterogeneity was partly caused by its very high permeability, which allowed fluid transfer and gas flow rapidly from the depressurisation front to the well. Modelling heterogeneity in lower permeability gas hydrate systems could investigate whether these sites have less erratic production as a result, as other potential gas hydrate production sites, such as the Nankai Trough, have permeability orders of magnitude lower than my modelling site (Yuan et al., 2017). Since my model indicated preferential gas flow avoiding areas of high gas hydrate saturation, adding a third dimension would explore how tortuous flow may become in heterogeneous systems, and whether this property can be exploited in production by artificially fracturing the formation.

Now that a preliminary network has been established in Alaska, and gas hydrate remains in the public consciousness (Brehmer, 2019), wider stakeholder engagement could provide more detail into Alaska's position on gas hydrate and gas resource development generally. Feedback from initial stakeholder meetings could be used to shape a second assessment that more accurately evaluates active projects, if there is interest in pursuing the resource. Expanding the stakeholder network, especially with more input from indigenous stakeholders, could provide further insight into under-represented groups, and explore the sharp division in indigenous society between those for and against resource development that I briefly encountered during fieldwork. The 2019 field study was conducted shortly after the inauguration of Governor Mike Dunleavy, and governmental priorities had not yet been established as a result. Further removed from this event, more government stakeholders may be willing to offer an accurate indication of their position on record. As the protocol style was not well suited to indigenous stakeholders, there is an open, although challenging, opportunity to co-produce an assessment approach that incorporates the oral tradition of the Inupiat and their emotional connectivity with the land.

During work in Alaska, gas hydrate was suggested as a possible energy source for isolated communities currently reliant on imported fuels. In these environments gas hydrate could improve energy reliability, and replace higher polluting fuels, if initial development costs are found. The North Slope government has invested heavily for small communities before, so could pursue an otherwise viable gas hydrate proposal with high economic costs. It is already uncertain whether gas hydrate is being dissociated by gas production at Utqiagvik, the largest city in the North Slope Borough, potentially providing precedent for these community projects. If a gas hydrate contribution could be proven, it would allow better understanding of the potential of gas hydrate in this environment, but research of the site has so far been limited. Commercial testing of gas hydrate production has focussed on large scale projects, so further research is necessary to establish if there are economic approaches to small scale production, and whether known production challenges, such as excessive water production, could be countered effectively in a small scale operation. As this scale of development has stakeholder and protocol support, it may provide a realistic pathway to gas hydrate commercialisation. This suggestion could be explored in other settings too, such as a small scale project supplying Tuktoyaktuk in Canada.

Throughout scenario analysis in Canada, Russia, and Japan I used weights derived from my fieldwork in Alaska in calculation. These values do not reflect local opinions, and it is important to establish how perceptions and priorities vary worldwide to understand the future of gas hydrate as a resource. A more participatory approach could be taken at any of my case study locations, as intended through the protocol design, involving stakeholders from alternative specification onwards. Equally, for individuals connected to these regions, deriving weights for the chosen criteria would be a relatively straightforward task that could refine the results presented in Chapter 5. Amongst my case studies, Japan is of particular interest for stakeholder engagement, as it is at the commercial frontier of gas hydrate development. The social structure in Japan is also very distinct to Alaska, so my scenario weights may be significantly different to real-world opinion. An assessment of the type presented here will need completion before Japanese commercial projects begin production, but preliminary work could simply apply the protocol more thoroughly, with a greater number of alternatives, criteria and stakeholders. Further afield, gas hydrate deposits in the Gulf of Mexico, the South China Sea and Indian Ocean have also been subject to scientific testing. These sites are further offshore proposals that can be explored using my protocol, and could provide the setting for future commercial comparisons, if my protocol presents favourable results.

Appendix A Numerical Modelling Data

Summary statistics for all 37 hydrate distribution models in the study

Model	1	2	3	4	5	6	7	8
Model type	Homo-geneous	Homo-geneous	Homo-geneous	Layered	Layered	Column	Column	Layered
Inter-cell variation	N/A	N/A	N/A	0.025	0.025	N/A	N/A	0.025
Mean	0.550	0.500	0.600	0.519	0.542	0.558	0.538	0.549
Ratio of mean to 55%	1.000	0.909	1.091	0.943	0.985	1.015	0.978	0.999
Median	0.550	0.500	0.600	0.563	0.588	0.604	0.559	0.579
Standard Deviation	0.000	0.000	0.000	0.190	0.168	0.167	0.161	0.157
Coefficient of variation	0.000	0.000	0.000	0.367	0.310	0.299	0.299	0.286
IQR	0.000	0.000	0.000	0.229	0.241	0.191	0.203	0.164
Skewness	1.001	1.001	-1.001	-1.073	-1.128	-1.310	-1.320	-1.633
RMS	0.550	0.500	0.600	0.552	0.567	0.582	0.561	0.571
Void%	0.000	0.000	0.000	3.600	3.350	1.520	3.880	3.960
Weighted Mean	0.550	0.500	0.600	0.534	0.558	0.552	0.546	0.552
Weighted Mean (half)	0.550	0.500	0.600	0.548	0.570	0.548	0.558	0.553

Model	9	10	11	12	13	14	15	16
Model type	Layered	Layered	Layered	Layered	Layered	Layered	Layered	Layered
Inter-cell variation	0.025	0.025	0.025	0.025	0.025	0.100	0.100	0.100
Mean	0.549	0.549	0.549	0.550	0.550	0.556	0.551	0.551
Ratio of mean to 55%	0.998	0.998	0.997	0.999	1.000	1.011	1.002	1.002
Median	0.609	0.604	0.604	0.592	0.588	0.579	0.587	0.579
Standard Deviation	0.185	0.191	0.194	0.168	0.177	0.168	0.187	0.176
Coefficient of variation	0.337	0.349	0.353	0.305	0.321	0.302	0.340	0.319
IQR	0.202	0.246	0.195	0.208	0.167	0.204	0.202	0.202
Skewness	-1.374	-1.101	-1.497	-1.353	-1.560	-1.233	-1.434	-1.364
RMS	0.579	0.581	0.582	0.575	0.578	0.581	0.582	0.578
Void%	4.720	3.800	6.850	3.810	5.260	4.190	6.700	5.410
Weighted Mean	0.549	0.553	0.547	0.561	0.554	0.555	0.549	0.541
Weighted Mean (half)	0.551	0.555	0.550	0.572	0.554	0.561	0.554	0.530

Model	17	18	19	20	21	22	23	24
Model type	Layered	Column	Column	Column	Layered	Layered	Random	Random
Inter-cell variation	0.100	0.020	0.020	0.020	N/A	N/A	N/A	N/A
Mean	0.548	0.437	0.587	0.595	0.542	0.532	0.467	0.440
Ratio of mean to 55%	0.997	0.795	1.067	1.081	0.986	0.967	0.850	0.800
Median	0.581	0.420	0.610	0.630	0.600	0.600	0.480	0.440
Standard Deviation	0.191	0.144	0.116	0.180	0.171	0.186	0.175	0.189
Coefficient of variation	0.348	0.330	0.198	0.303	0.315	0.350	0.374	0.429
IQR	0.221	0.220	0.040	0.140	0.250	0.250	0.290	0.300
Skewness	-1.398	-0.597	-4.381	-2.486	-1.580	-1.540	-0.260	-0.348
RMS	0.580	0.460	0.598	0.621	0.569	0.564	0.499	0.479
Void%	7.080	3.050	3.430	7.240	4.950	7.000	1.900	5.330
Weighted Mean	0.534	0.502	0.584	0.557	0.543	0.528	0.467	0.454
Weighted Mean (half)	0.528	0.548	0.576	0.522	0.539	0.520	0.462	0.465

Model	25	26	27	28	29	30	31	32
Model type	Random	Random	Layered	Layered	Layered	Layered	Layered	Layered
Inter-cell variation	N/A	N/A	0.025	0.025	0.025	0.025	0.025	N/A
Mean	0.447	0.448	0.554	0.532	0.510	0.532	0.510	0.386
Ratio of mean to 55%	0.812	0.814	1.007	0.967	0.927	0.967	0.928	0.702
Median	0.460	0.450	0.604	0.593	0.592	0.593	0.592	0.400
Standard Deviation	0.195	0.187	0.173	0.200	0.222	0.200	0.222	0.279
Coefficient of variation	0.437	0.417	0.312	0.376	0.435	0.376	0.435	0.722
IQR	0.310	0.290	0.217	0.245	0.291	0.245	0.291	0.645
Skewness	-0.436	-0.402	-0.969	-1.087	-1.019	-1.086	-1.018	-0.367
RMS	0.487	0.485	0.580	0.568	0.556	0.568	0.557	0.476
Void%	6.170	5.180	0.000	3.960	7.840	3.960	7.920	30.770
Weighted Mean	0.445	0.449	0.566	0.544	0.522	0.545	0.524	0.386
Weighted Mean (half)	0.439	0.446	0.577	0.555	0.533	0.556	0.534	0.386

Model	33	34	35	36	37
Model type	Layered	Layered	Layered	Column	Random
Inter-cell variation	N/A	N/A	N/A	N/A	N/A
Mean	0.474	0.371	0.540	0.540	0.540
Ratio of mean to 55%	0.862	0.674	0.982	0.982	0.982
Median	0.600	0.400	0.592	0.592	0.592
Standard Deviation	0.231	0.265	0.171	0.171	0.171
Coefficient of variation	0.487	0.715	0.317	0.317	0.317
IQR	0.300	0.595	0.157	0.157	0.157
Skewness	-1.061	-0.399	-2.019	-2.019	-2.019
RMS	0.527	0.456	0.567	0.567	0.567
Void%	15.380	30.770	7.010	7.010	7.010
Weighted Mean	0.474	0.371	0.549	0.544	0.547
Weighted Mean (half)	0.474	0.371	0.557	0.545	0.556

Pearson correlation coefficients and confidence values between hydrate saturation summary statistics and gas production rate at 5 year intervals, separated by hydrate distribution model type.

	Production time (years after start)					
	5	10	15	20	25	30
Correlation coefficients						
All models						
Mean	0.6612	0.5421	0.6613	0.68	0.5618	0.5049
Weighted Mean	0.7064	0.6094	0.7684	0.7841	0.628	0.5343
Weighted Mean (half)	0.6952	0.6203	0.8017	0.8168	0.6459	0.5327
Layered models						
Mean	0.5999	0.551	0.6704	0.7177	0.5039	0.4939
Weighted Mean	0.6529	0.5735	0.7431	0.793	0.5605	0.5108
Weighted Mean (half)	0.6683	0.5794	0.7755	0.827	0.596	0.5194
Columnar models						
Mean	0.8689	0.1016	0.0021	0.0141	0.3366	0.7545
Weighted Mean	0.8041	0.353	0.2536	0.118	0.3217	0.6936
Weighted Mean (half)	0.0606	0.5057	0.5469	0.181	-0.0385	0.0164
Random models						
Mean	0.9724	0.8332	0.8203	0.9214	0.8573	0.887
Weighted Mean	0.9392	0.8927	0.7928	0.9081	0.8703	0.935
Weighted Mean (half)	0.8866	0.9315	0.7521	0.8771	0.8641	0.9606

	Production time (years after start)					
	5	10	15	20	25	30
Confidence values						
All models						
Mean	2.00E-05	0.0009	2.00E-05	1.00E-05	0.0005	0.0023
Weighted Mean	3.00E-06	0.0001	1.00E-07	4.00E-08	0.0001	0.0011
Weighted Mean (half)	5.00E-06	0.0001	1.00E-08	4.00E-09	4.00E-05	0.0012
Layered models						
Mean	0.0025	0.0064	0.0005	0.0001	0.0142	0.0166
Weighted Mean	0.0007	0.0042	0.0001	0.0000	0.0054	0.0128
Weighted Mean (half)	0.0005	0.0038	0.0000	0.0000	0.0027	0.0111
Columnar models						
Mean	0.0247	0.8481	0.9968	0.9789	0.5142	0.0830
Weighted Mean	0.0517	0.4924	0.6277	0.8238	0.5341	0.1264
Weighted Mean (half)	0.9092	0.3061	0.2614	0.7315	0.9423	0.9755
Random models						
Mean	0.0055	0.0797	0.0889	0.0261	0.0633	0.0448
Weighted Mean	0.0178	0.0415	0.1096	0.0330	0.0550	0.0197
Weighted Mean (half)	0.0451	0.0213	0.1425	0.0507	0.0589	0.0093

Pearson correlation coefficients and confidence values between hydrate saturation summary statistic and gas production rate at 5 year intervals. Models are grouped by difference between heterogeneous model mean hydrate saturation and homogeneous model 55% hydrate saturation. Categories with increasing range include all models from narrower categories.

	Production time (years after start)					
	5	10	15	20	25	30
Correlation coefficients						
55%±0.5%						
Mean	0.0831	0.4213	0.5717	0.4733	0.2663	0.373
Weighted Mean	0.4889	0.1557	0.7415	0.7652	0.2374	0.0354
Weighted Mean (half)	0.4693	0.11	0.6119	0.6507	0.1553	-0.0562
55%±1%						
Mean	-0.0387	-0.0181	0.1685	-0.2697	-0.2523	-0.1894
Weighted Mean	0.4169	0.1129	0.7146	0.5631	0.2273	0.1554
Weighted Mean (half)	0.3854	0.1213	0.6334	0.5888	0.3029	0.2351
55%±4%						
Mean	-0.0117	0.21	0.1589	0.04	0.0328	0.2373
Weighted Mean	0.1063	0.2892	0.4963	0.4278	0.2702	0.3533
Weighted Mean (half)	0.2185	0.2739	0.6174	0.6268	0.4249	0.4034
55%±11%						
Mean	0.4769	0.4674	0.5585	0.5382	0.4033	0.3667
Weighted Mean	0.5752	0.4822	0.6821	0.6754	0.4819	0.405
Weighted Mean (half)	0.5917	0.4488	0.7123	0.7208	0.5087	0.4119

	Production time (years after start)					
	5	10	15	20	25	30
Confidence values						
55%±0.5%						
Mean	0.8195	0.2253	0.0842	0.1671	0.4571	0.2884
Weighted Mean	0.1516	0.6675	0.0141	0.0099	0.5090	0.9227
Weighted Mean (half)	0.1712	0.7623	0.0601	0.0416	0.6683	0.8775
55%±1%						
Mean	0.8827	0.9449	0.5179	0.2951	0.3287	0.4666
Weighted Mean	0.0960	0.6660	0.0013	0.0186	0.3803	0.5515
Weighted Mean (half)	0.1265	0.6428	0.0063	0.0129	0.2372	0.3638
55%±4%						
Mean	0.5777	0.3136	0.4480	0.8496	0.8761	0.2533
Weighted Mean	0.6131	0.1609	0.0116	0.0329	0.1914	0.0832
Weighted Mean (half)	0.2940	0.1852	0.0010	0.0008	0.0343	0.0456
55%±11%						
Mean	0.0077	0.0092	0.0013	0.0022	0.0271	0.0463
Weighted Mean	0.0009	0.0070	0.0000	0.0000	0.0070	0.0264
Weighted Mean (half)	0.0006	0.0129	0.0000	0.0000	0.0041	0.0237

Appendix B Detail of Alaska Gas Hydrate Exploitation Alternatives as Supplied to Stakeholders

Introduction

This document provides detailed information about different potential schemes for exploiting gas hydrate at the Alaska North Slope. These alternatives are summarised in the impact matrix presented in the main text (Table 4.1). Development compounds in successive alternatives, meaning the impacts described for alternative 2 are in addition to those described for alternative 1 and so on, except where elements of different alternatives contradict each other. Four different alternatives are described:

- Alternative 1: Gas produced solely for use within the Prudhoe Bay oilfield.
- Alternative 2: Operations expanded to supply gas throughout Alaska.
- Alternative 3: Additional gas produced for an export market.
- Alternative 4: Gas hydrate is not exploited.

Alternatives 2 and 3 propose two different routes for distributing gas from the North Slope throughout Alaska (Figure 4.3). The first travels due south to the Cook Inlet, the second follows the route of the Trans-Alaska Pipeline System (TAPS), a large crude oil pipeline connecting North Slope production to Valdez port (Alaska Gasline Development Corporation, 2017; Alaska Gasline Port Authority, 2016). The due south route is discussed in alternative 2, the TAPS route in alternative 3, with Valdez the export port. Whether this port is chosen is under debate (Brehmer, 2018; DeMarban, 2018, 2017). Creation of a large gasline would likely be motivated by development of conventional gas as well as gas hydrate, although only the impacts from developing gas hydrate at the field are discussed here.

Development would originate at promising test wells accessible from existing infrastructure to minimise costs, from where expansion would be dictated by demand (Wilson et al., 2011). New wells drilled would be standard gas production wells specialised for gas production from Arctic hydrates with a strong focus on temperature control. Wells will be situated on ice or gravel pads to prevent unintended permafrost thawing from industrial heating used to prevent hydrate reforming and blocking the system (Ashford et al., 2012a, 2012b; Moridis et al., 2009). A mesh screen would be used to limit fine input into the well which has hindered previous production attempts (Kurihara et al., 2011), and extra pumping facilities would be needed to handle the high water production of hydrate development (Walsh et al., 2009). This water would then be treated before being transported off site for disposal or reinjected into local formations following existing environmental regulations (Ashford et al., 2012a, 2012b; Denman and Starr, 1992).

Criteria

We quantify impacts against individual criteria consistently across the four alternatives. We summarise the broad approaches takes for each criterion here before discussing details of each alternative individually.

Resource

Gas Production

For each alternative total gas production is calculated from multiplying gas production from our numerical model of a gas hydrate well by the number of wells in our field. We have used well logging data from the 2011 stratigraphic test at Mt Elbert (Collett et al., 2011a, 2011b) to build a hypothetical 2D reservoir model using TOUGH+Hydrate multi-phase flow simulation software (Moridis, 2008). We produced gas from gas hydrate by depressurisation following a depressurisation profile based on that used in the 2008 Mallik depressurisation test in north-west Canada (Kurihara et al., 2011).

Economic

Total Cost

Project total cost as measured is the initial cost to develop the necessary infrastructure. We rely on proposals for similar conventional gas projects for cost estimates for the major facilities and pipeline routes. Both pipeline routes and processing facilities have been considered for conventional gas development (Alaska Gasline Development Corporation, 2013; PFC Energy, 2006). For well development costs we use a high end estimate from the range of current and projected well costs for development at the North Slope (Thomas et al., 2007). Where necessary we correct these prices for inflation (Bureau of Labor Statistics, 2018).

Market

Estimates of market price for hydrate use price projections for natural gas in the different markets we consider (Fay et al., 2011; Montgomery et al., 2014; U.S. Energy Information Administration, 2018)

Taxation

For most alternatives there are two components to tax income: 1) property tax on the pipeline and other production facilities and 2) production tax on the produced gas. We calculate property tax on the facility values derived from development costs using the current legislation used for the oil and gas industry (Alaska Department of Revenue, 2018b). We calculate production tax on the modelled volumes of gas produced following current legislation for conventional gas (Alaska Department of Revenue, 2018a), as no hydrate-specific tax legislation exists.

Social

Employment

For each alternative we quantify only permanent employment. For major facilities and pipeline maintenance we use estimates from other proposals with similar infrastructure (Alaska Department of Labor and Workforce Development, 2018b; Alaska Gasline Development Corporation, 2014). To estimate employment from new wells we used employment statistics (Alaska Department of Labor and Workforce Development, 2018a) and time evolution of the number of wells (Alaska Oil and Gas Conservation Commission, 2018) to estimate how many oil and gas jobs are created per new well.

Recreation

We estimate recreation impact from spatial analysis as new infrastructure can provide access routes to recreation sites, increasing the number of people using a resource, and also directly cause a decline in quality of recreation assets reliant on the natural environment, such as hunting. For the location of recreation sites we use a publically available database (Recreation.gov, 2018) and Bureau of Land Management maps for the main Alaska recreational areas (Bureau of Land Management, 2017).

Cultural Assets

To estimate impact on cultural assets we use spatial analysis of proximity of the pipeline route to three different measures of different cultural assets. Industrial development can affect subsistence over a wide range beyond the immediate pipeline vicinity, as Alaska Natives can travel over 150 miles to hunt, especially using motorised vehicles such as ATVs, snowmobiles and motorboats (Brinkman et al., 2014; Jorgensen, 1990). We consider the impacted indigenous population by using population estimates for settlements within subsistence range of the pipeline route (Alaska Department of Labor and Workforce Development, 2017). As caribou are a major subsistence resource we also consider the size of caribou herds that could be impacted by a pipeline development within their traditional range, using previous inventories of the species (Harper and McCarthy, 2015). Finally, we also consider the number of designated sites that may be impacted by using previous impact analyses for sections of the development routes (Shaw Alaska, 2005; United States Army Corps of Engineers, 2012c; U.S. Department of the Interior, 2002).

Environmental

Pollution

Although there are many different pollutants that could be produced in hydrate developments we choose to focus on CO_2 emissions as this can be quantified and is readily comparable for all alternatives. For production emissions we use the environmental impact statement for a comparable unconventional gas development in the continental United States (NYSDEC, 2011). We use environmental impact statements for other project proposals in Alaska to estimate emissions from the major proposed facilities (OASIS Environmental, 2004; United States Army Corps of Engineers, 2012e).

Accidents

To quantify the impact of accidental infrastructure failures we use estimates of the percentage of gas production that is lost taken from engineering assessments on existing infrastructure in other gas developments (Howarth et al., 2011; Lowell et al., 2013).

Habitat Impact

For habitat impact we consider the number of species whose habitat ranges are coincident with the proposed development. We consider impact on the ranges of 69 mammals (IUCN, 2018), sites identified as important for bird species living or migrating in the state (Audubon Alaska, 2015) and rivers used by anadromous fish (Alaska Department of Fish and Game, 2018).

Aesthetic Impact

We measure aesthetic impact by the area of land that has a specific designation for beauty or environmental significance that is within sightline distance of new infrastructure. We consider aesthetic impact lower where the new infrastructure is developed alongside existing infrastructure that has already changed the natural character of the location. Areas considered are National Parks (National Park Service, 2018), National Grassland (United States Department of Agriculture, 2018), National Forests (United States Department of Agriculture, 2018), Wilderness Areas (Wildland Fire Decision Support System, 2014), State Parks (Alaska Department of Natural

Resources, 2012) and Scenic Byways (Alaska Department of Transportation and Public Facilities, 2007).

Alternative 1 – Gas only used within the local oilfield

Economic

Total alternative cost involves creation of a series of gas hydrate production wells and a gas conditioning facility in a small area within current development at the North Slope. The small scale of development here may be able to be accommodated by existing facilities, but we assumes a general increase in gas development at the North Slope necessitates new facilities.

Since this alternative does not include any broader distribution infrastructure the target market is limited to the oilfield, where gas is used to maintain reservoir pressure, enhance recovery and fuel oilfield facilities (Alaska Department of Revenue, 2006; Wilson et al., 2011). There are 75-135 trillion cubic feet of conventional natural gas at the North Slope that could be developed instead of gas hydrate (Attanasi and Freeman, 2009), and there is currently a significant oversupply to the North Slope from conventional gas (Thomas et al., 2007). Gas hydrate derived gas would need to compete on this market to be developed. Market value for the produced gas is therefore the projected industrial gas price at the North Slope (U.S. Energy Information Administration, 2018).

Hydrate development itself will not directly provide significant tax revenue, with the main tax revenue from property tax on the gas conditioning facility (Alaska Department of Revenue, 2018b). Gas enhanced recovery will allow TAPS flow to exceed minimum levels for longer by maintaining sufficient oil production levels to allow continued export. This will prolong the period for which oil and gas tax revenue remains around present day levels, although we do not consider this revenue in our tax income estimate (Alaska Department of Revenue, 2018a).

Social

There would be a small number of new, well paid, skilled, long term positions created by new well development and the gas conditioning facility. These positions could be occupied by individuals moving from oil production, or skilled workers from out of state as are currently employed in conventional oil and gas development at Prudhoe Bay (Bradner, 2011; Orians et al., 2003).

The affected area will be very small and within that already disturbed by development at the North Slope so there will be very little new impact to recreation or cultural assets. There are no designated recreation sites close enough to the field to be impacted. For cultural assets Nuiqsut is the only settlement near the field (Alaska Department of Labor and Workforce Development, 2017), but the Central Arctic and Teshekpuk caribou herds both migrate in the region (Harper and McCarthy, 2015).

Environmental

New facilities would create air pollution and solid waste, and the supply transport network would also cause air pollution and dust. Due to the small development scale of this alternative CO_2 emissions would not increase significantly.

Well equipment failure could lead to methane release (Vedachalam et al., 2017). Methane is over 20 times more effective than CO_2 at absorbing infrared radiation on a molar basis and by weight methane is 66 times more effective (Wuebbles and Hayhoe, 2002). Therefore, any methane leak could have negative climatic impacts, which would be felt over a broad area (Sanchez and Mays, 2015). Well failure rates are highly variable depending on location, although modern wells are generally less likely to fail (Michanowicz et al., 2017). Methane leakage is estimated between 0.4-10% of production in conventional operations from source to end use (Sanchez and Mays, 2015). Using unconventional shale gas production in the contiguous US as an analogous recent gas development, 2.5-3.5% of these wells have experienced some form of integrity failure (Davies et al., 2014).

Gas hydrate wells would be within the existing Prudhoe Bay footprint causing no expansion of the area of disruption to plants or animals. The lack of expansion would also cause no further aesthetic impact, as new development is contained within the developed oilfield area.

<u>Alternative 2 – Gas used domestically within the state of Alaska</u>

Estimated well density is around one well per 650 acres (Wilson et al., 2011). Gas conditioning facilities would need expansion from current facilities as this project is much larger in scale (Alaska Gasline Development Corporation, 2014).

Distribution from the North Slope will use a 737-mile pipeline running due south to the Cook Inlet, with a 35-mile spur allowing gas to be delivered to Fairbanks (Alaska Gasline Development Corporation, 2013; Meyer and Richards, 2017). This pipeline follows the TAPS route in the north of the state, but diverges to follow a more direct route to Anchorage along the edge of Denali National Park (Figure 4.3). At the Cook Inlet gas would be distributed through the existing pipeline network, although this was built in the 1960s and may need renovation to handle continued long-term use (Boettger, 2017). Maintenance facilities would be built at the pipeline ends (Alaska Gasline Development Corporation, 2013).

Economic

Development costs include drilling wells over a larger area of the North Slope and creating gas processing facilities to enable gas produced at the North Slope to be used domestically and industrially throughout the state. Distribution from the North Slope will use a 737-mile pipeline costing \$8.4 billion ± 30% (2018\$) (Alaska Gasline Development Corporation, 2013; Meyer and Richards, 2017).

Gas production in this alternative is used to supply the Alaskan domestic market at projected prices (Fay et al., 2011). Offlets from the pipeline would allow gas distribution throughout rural Alaska, although the pipeline is primarily routed to supply the major markets at Fairbanks, Anchorage and the Cook Inlet. The Cook Inlet market is currently met by locally produced gas, but this supply is declining and cannot continue to meet demand (Stokes et al., 2010). Two major potential Cook Inlet users are the Agrium Kenai nitrogen plant and the Kenai LNG plant (McDowell Group, 2015) and a reliable gas supply would increase the likelihood of either reopening (Boettger, 2018a; Cashman, 2018). Fairbanks is currently supplied LNG by truck from the south, which has allowed 1000 homes and businesses to switch fuel to gas (Brehmer, 2016). Greater gas availability could encourage wider conversion from other, more highly polluting, fuel sources to gas (Liang et al., 2012).

Estimated tax revenue is derived from production tax on the North Slope gas used in state (Alaska Department of Revenue, 2018a), and property taxes on the developed production infrastructure (Alaska Department of Revenue, 2018b). This alternative derives most tax revenue from property tax on the pipeline route and North Slope gas conditioning facilities.

Social

Peak employment during construction is estimated at 5,500 (United States Army Corps of Engineers, 2012a). Construction jobs would be short term and seasonal which may facilitate non-resident hire, especially if contracted to external firms (Jorgensen, 1990). New permanent jobs would be spread between the oilfield, gas processing facilities and pipeline maintenance. These jobs may benefit the local community, although unemployed persons may not be positioned or sufficiently skilled to fill new positions, which would again necessitate external hire (Department of Labor and Workforce Development, 2017b). 1800 persons are employed to maintain TAPS and adding a second pipeline will create more maintenance positions (Alyeska Pipeline Service Company, 2016). Long term employees would be spread along the pipeline and no single community would experience a large population influx (Schultz, 2013; United States Army Corps of Engineers, 2012a).

New rights of way could improve access to natural resources used for recreation, although if visitors reach unsustainable levels overuse of the resource may cause resource quality to decline (United States Army Corps of Engineers, 2012b). Potentially unsustainable activities such as hunting are well regulated throughout the state (Department of the Interior, 1991; United States Army Corps of Engineers, 2012b), and new access routes for this alternative would only deliver a limited area beyond assets already accessible using transport infrastructure developed alongside the TAPS (Bureau of Land Management, 2017; Recreation.gov, 2018).

Native communities may see declines in resource availability or quality due to increased competition if development facilitates access for other resource users, such as sport hunters (United States Army Corps of Engineers, 2012d). Industrial noise may divert animals from traditional habitats, which makes them harder to locate for subsistence hunters using inherited knowledge (United States Army Corps of Engineers, 2012d). Likely affected communities will have some preparation and resiliency to development having experienced the effects of TAPS for a long duration (Bureau of Land Management, 2002). In addition to those impacted at the Arctic Slope, the Delta, Denali and Nelchina caribou herds could also be impacted on the pipeline route.

Environmental

This alternative will make gas more readily available to communities throughout Alaska which could allow them to switch from other, higher polluting, fuel sources. Switching fuel from diesel or fuel oil to gas will reduce harmful emissions and improve air quality, with gas producing 99% less SO2, 99% less PM10, 29% less NOx and 24% less CO_2 per BTU all of which have a negative impact on air quality (PDC Harris Group, 2011). However, we consider well and facility CO_2 emissions during gas production and transport only, as quantifying the number of end users who would switch fuel and the associated climatic impact is beyond the means of our study.

Within the US there are 573 reported incidents on gas pipelines per year, and 5.6 on the small existing Alaska gas network (PHMSA, 2018). The remoteness of the proposed pipeline, coupled with difficult weather and terrain mean it may leak significantly before repair (Boettger, 2018b; WWF, 2008) and leaked gas could ignite if there is a trigger, causing possible equipment loss and casualties (Han and Weng, 2010). The most likely causes of pipeline failure are external interference and material defects, which cannot be eliminated (Jo and Ahn, 2005; Shan et al., 2017).

Pipeline construction would directly damage vegetation in a long, narrow corridor and vegetation regrowth would be restricted to allow pipeline maintenance (Alaska Pipeline Project, 2011).Water courses on the route could be used during construction and may see increased sediment input, potentially decreasing water quality (Allan and Castillo, 2007; Cretaz and Barten, 2007). The pipeline would be elevated to prevent it blocking wildlife, although it may still form a barrier as a result of drifting snow which could impede animal migration routes (U.S. Department of the Interior, 2014). The pipe would run chilled to prevent permafrost thawing, which could cause freezing leading to land deformation or ice damming in water courses if poorly controlled and insulated (Alaska Gasline Development Corporation, 2013; United States Army Corps of Engineers, 2012f; Wu et al., 2010). Conversely, construction heat could promote thawing of frozen ground, which may cause subsidence (Liu et al., 2014; Raynolds et al., 2014). Since the pipeline crosses the state, it will affect a number of different species' habitats across many ecosystems. Where this pipeline follows the TAPS the impacts from both pipelines will be greater than either alone, but there may be greater impact in the south section of the pipeline, where this pipeline affects less developed habitat near Denali.

Where the pipeline route follows the edge of Denali National Park, it may have a visual impact, especially during construction (United States Army Corps of Engineers, 2012g). Elsewhere the aesthetic impact of this project is lessened by its proximity to the TAPS, as this has already caused aesthetic disruption to the area.

<u>Alternative 3 – Gas produced for export via a South Alaskan LNG terminal</u>

Well density in this alternative would increase from that of alternative 2 to one per 160 acres to maximise exploitation of the resource (Wilson et al., 2011). The overall developed area and supporting infrastructure including roads, pipelines and buildings would grow as the site grows, expanding progressively from existing development. The project requires an 806-mile pipeline connecting the North Slope to the port of Valdez (Figure 4.3). The gas pipeline route follows the TAPS route to minimise disruption to undeveloped areas and make us of existing infrastructure, with a spur from the main pipeline to the Cook Inlet following the Glenn Highway. Port facilities at Valdez will be improved to export LNG with three processing units and storage for 240,000 m3 of natural gas, and berths to accommodate large (>200,000 m3 capacity) LNG carriers (Alaska Gasline Development Corporation, 2017).

Economic

The estimated project cost includes construction of over 800 wells, a gas processing facility, a pipeline connecting the North Slope to Valdez port in the south, and liquefaction and export facilities.

The Alaska export pipeline and distribution network here is still designed to oversupply the state, in addition to fulfilling export contracts (Meyer et al., 2018). Akin to limitations on oil exports, LNG exports may be restricted for energy security purposes (Bernstein et al., 2016). If there is no legislative restriction the main export target would be the Asian sphere, where there are several possible markets including:

- Japan. In response to the Fukushima Daiichi nuclear disaster, Japanese national policy has shifted to increase gas use, but current domestic exploitation only meets 6% of demand, creating a large import market (Agency for Natural Resources and Energy, 2016; Hong et al., 2013). Japan also has significant gas hydrate research and will likely have commercial operations before the North Slope, which may reduce demand by the time North Slope development occurs (Oyama and Masutani, 2017).

- China. China is the world's largest energy consumer (BP, 2017). Demand has previously been met by using coal, but natural gas consumption has grown at 15.3% per year since 2000 to meet growing demand and limit harmful emissions (Zhou et al., 2017). China has invested heavily in unconventional hydrocarbons including methane hydrates (Jia et al., 2012), especially offshore where small scale testing has occurred (Associated Press, 2017; Li et al., 2010; Wu et al., 2005). Although domestic conventional gas and gas hydrate projects would supply some gas, very high demand would likely mean a suite of suppliers of gas to China are required.

- South Korea. South Korea is highly industrialised needing significant energy to fuel an export focussed economy (BP, 2017). Previously demand was met by coal and oil, but gas is being increasingly used due to environmental considerations (Raval, 2017).

- Taiwan. Taiwan economically similar to South Korea. Since 2008 total energy demand has been consistent, but LNG consumption has increased by 70% (BP, 2017; Rogers, 2016). Domestic gas production has declined in the same period, leading to reliance on imports (Bureau of Energy, MOEA, 2017).

Projected market price is estimated from future projections of gas price in these markets and economic analyses of gas export from an Alaskan gas project (Montgomery et al., 2014; U.S. Energy Information Administration, 2018)

In addition to production and property tax, gas would also be subject to an export tax in this alternative (U.S. Department of Energy, 2015). Again this alternative derives most tax revenue from property tax on new infrastructure, including the expanded facilities at Valdez. The existing port in Valdez provide 88% of borough property tax revenue, $43.4 million (McDowell Group, 2017).

Social

Peak construction employment projected is 11,850, although this will only last for a couple of years at most, followed by much smaller long term employment (Alaska Gasline Development Corporation, 2017). Total permanent employment includes the port, facilities at the North Slope and well and pipeline upkeep and maintenance. Most new long-term jobs will be in Valdez port operation, which are the lowest paying jobs related to oil and gas industry, paying $16 per hour, so these jobs do not provide as much benefit as others in the same industry (Department of Labor and Workforce Development, 2017a).

Recreation and cultural assets affected by this project span the state, but have already been affected by development of the TAPS on the same route and so may be more resilient to future disturbances. Increasing resource development near these assets has the potential to increase demand on them, which may adversely affect their quality if more individuals can access the area.

Due to the Exxon Valdez spill, local indigenous communities around Prince William Sound are sometimes more cautious of the extractive sector than elsewhere in Alaska (Picou and Martin, 2007), and so are more likely to oppose industrial expansion. The spill also negatively affected stocks of some species used for subsistence, which have not recovered, so these species would have low resiliency to future disruption, the risk of which is increased by bringing further development to the region (WWF, 2008). We identify twelve villages within 50 km of the pipeline route (Alaska Department of Labor and Workforce Development, 2017) and identify five distinct caribou herds whose habitat may be affected by this pipeline route, although these herds exist alongside the TAPS (Harper and McCarthy, 2015). We also identify over a thousand sites of cultural significance that may be impacted, but again these have already been impacted similarly by the TAPS (Shaw Alaska, 2005; U.S. Department of the Interior, 2002).

Environmental

2017 annual Valdez port traffic was 287 vessels (Bureau of Transportation Statistics, 2018), and LNG export is predicted to double traffic, with 200 – 360 container ships per year (Alaska Gasline Development Corporation, 2017). Shipping causes most emissions in Valdez, which has adversely affected local air quality (Porter, 2009), and increased shipping will cause further air quality deterioration. Treated ballast water will continue to be discharged from shipping at Port Valdez, however modernisation of tankers and port facilities will decrease discharge per ship or facility, although overall discharge will increase (Bureau of Land Management, 2002). Our estimate of CO_2 emissions includes infrastructure operation and increased shipping (OASIS Environmental, 2004; United States Army Corps of Engineers, 2012e).

This alternative has spill risk from the well, pipeline, processing facilities and port. In a breach gas will vaporise and may ignite, which puts risk blowing out the TAPS (Hightower et al., 2005). Risk of negative impacts is higher for intentional damage, as safety standards minimise fire risk in inadvertent breaching (Hightower et al., 2004), and two parallel pipelines present a larger target. Even with additional concern following the 1989 Exxon Valdez incident in the inlet, spills continue in the region (Harball, 2018), so inadvertent release must be expected. However there have only been eight marine LNG incidents in the past 40 years, none of which has led to a fire, so an accident of this type is very unlikely (Hightower et al., 2004).

By developing a new pipeline following the TAPS route impact on the natural environment will be minimised. We include marine mammals such as Harbour seals, sea otters, killer whales and Steller sea lions that inhabit the Gulf of Alaska alongside the previously considered terrestrial mammals in our impact analysis (IUCN, 2018; OASIS Environmental, 2004). Increased shipping would put additional pressure on these species, and port expansion would cause habitat loss in a localised area. Following the TAPS route also lessens the aesthetic impact of development, as the natural aesthetic has been disturbed by a very similar structure.

Alternative 4 – Gas Hydrate is not exploited from the Alaska North Slope

Without utilising gas to enhance recovery, North Slope oil production is projected to decline year on year (Alaska Department of Revenue, 2017). Conventional gas would continue to be used at the North Slope and in state until it runs out. In this alternative there is no distribution infrastructure for conventional gas from the North Slope so this gas remains trapped, the North Slope is over supplied, and gas hydrate is not pursued.

There are a number of social and environmental consequences associated with the end of operations at the North Slope, and as this alternative includes no new gas development, Prudhoe Bay operations will cease fastest in this alternative. However, the end of development at Prudhoe Bay is inevitable in all alternatives due to the finite nature of the resource being developed.

Economic

Without developing the North Slope for gas supply declining Cook Inlet reserves will remain the only domestic supply in the south of the state, causing Alaskan natural gas prices to nearly double by 2030, even while gas prices in the contiguous United States remain low (Fay et al., 2011). The cheap gas supplying the remainder of the U.S. cannot practically and economically be distributed throughout Alaska, so we rely on Alaska domestic price projections without North Slope gas development (Montgomery et al., 2014).

This alternative has no cost associated as there is no new large scale infrastructure. Without infrastructure development, there is no new tax revenue.

Social

There is no new employment created, and no expansion of development impacting cultural or recreation resources.

Environmental

For the no development alternative there is no new infrastructure or industrial expansion of the currently developed area at the North Slope so we do not assign any impact to habitat or aesthetic, and there would be no increase in operational or accidental emissions.

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Appendix C **Stakeholder Interview Outline**

Part 1 Broad contextual questions (15 minutes)

What has been your experience with the Alaskan oil and gas industry, up to this point?

Before I contacted you how familiar were you with natural gas hydrates?

How do you define your role within the state of Alaska?

Part 2 Weighting (10 minutes)

These cards represent different aspects of the problem which are assessed. Can you please order them from most to least important to you in making the decision between development alternatives. You can represent criteria as equally important by grouping them together.

Is there anything you think I am missing?

Part 3 Thresholds (20-25 minutes)

Using the alternatives provided can you define the difference between alternatives which would cause you to choose one over another?

Now for the other extreme. Is there a point at which an alternative would become unacceptable, judged on this criterion alone?

How confident are you in these values?

From the information you have provided, what would you expect your ranking of project alternatives to be?

Closing – if not already covered (10 minutes)

Would you support further industrial development in the Alaska Arctic? Why/why not?

Appendix D Messoyakha Lifespan Estimate Calculation

Field defining parameters (Makogon and Omelchenko, 2013):

Current total gas in place:	22.3 x10^9 m^3/year
Of which is free gas:	15.7 x10^9 m^3/year
Of which is solid gas hydrate:	6.6 x10^9 m^3/year
Current production rate per well:	0.1 x10^9 m^3/year
Estimated gas hydrate production rate per well:	0.035 x10^9 m^3/year

I assume that gas hydrate is providing pressure support to the well, so production begins to decline once all solid hydrate has been removed from the system. Rate of hydrate loss is equivalent to the rate of gas production, as gas from hydrate replaces the gas produced. Although historic gas production has been a hydrate-derived/free-gas mix, my alternatives focus on producing from the hydrate bearing strata.

For alternative 1:

20 wells

6.6 / [(20 x 0.035) + 0.1] = 8 years

For alternative 2:

12 wells

6.6 / [(12 x 0.035) + 0.1] = 13 years

For alternative 3:

6.6 / 0.1 = 66 years

After each of these times I apply a decay curve using the approach of Söderbergh et al., (2010). I calculate a decay coefficient using the last two years in the production history of the field, when the field was producing commercially, 1973 and 1974, as my simulated production is at a constant level (Makogon and Omelchenko, 2013). From this my decay coefficient is a 22% decline rate, high for a Russian field, but within the range of reported values (4 – 25%) (Söderbergh et al., 2010). The production profiles in **Figure 6.2** appear dramatic due to the low production rates, so declines to no production are abrupt.

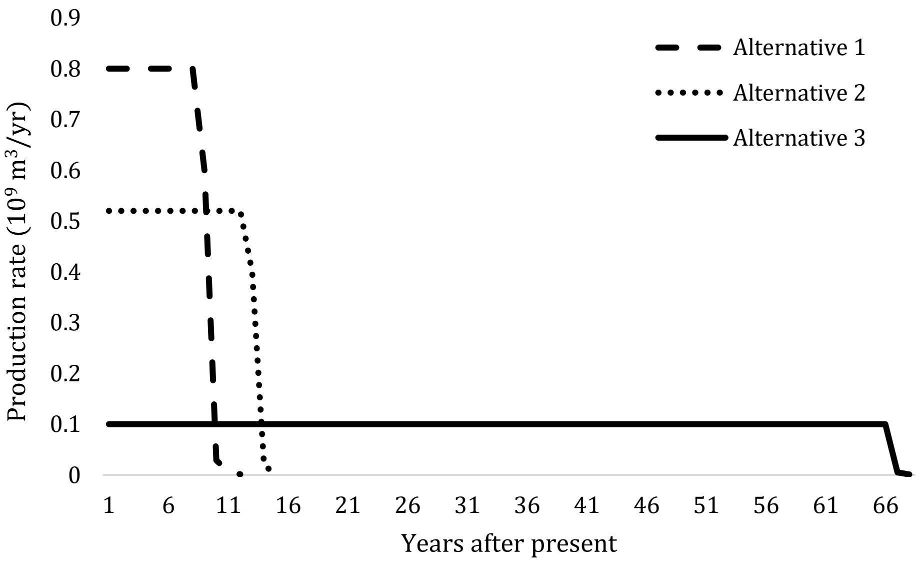
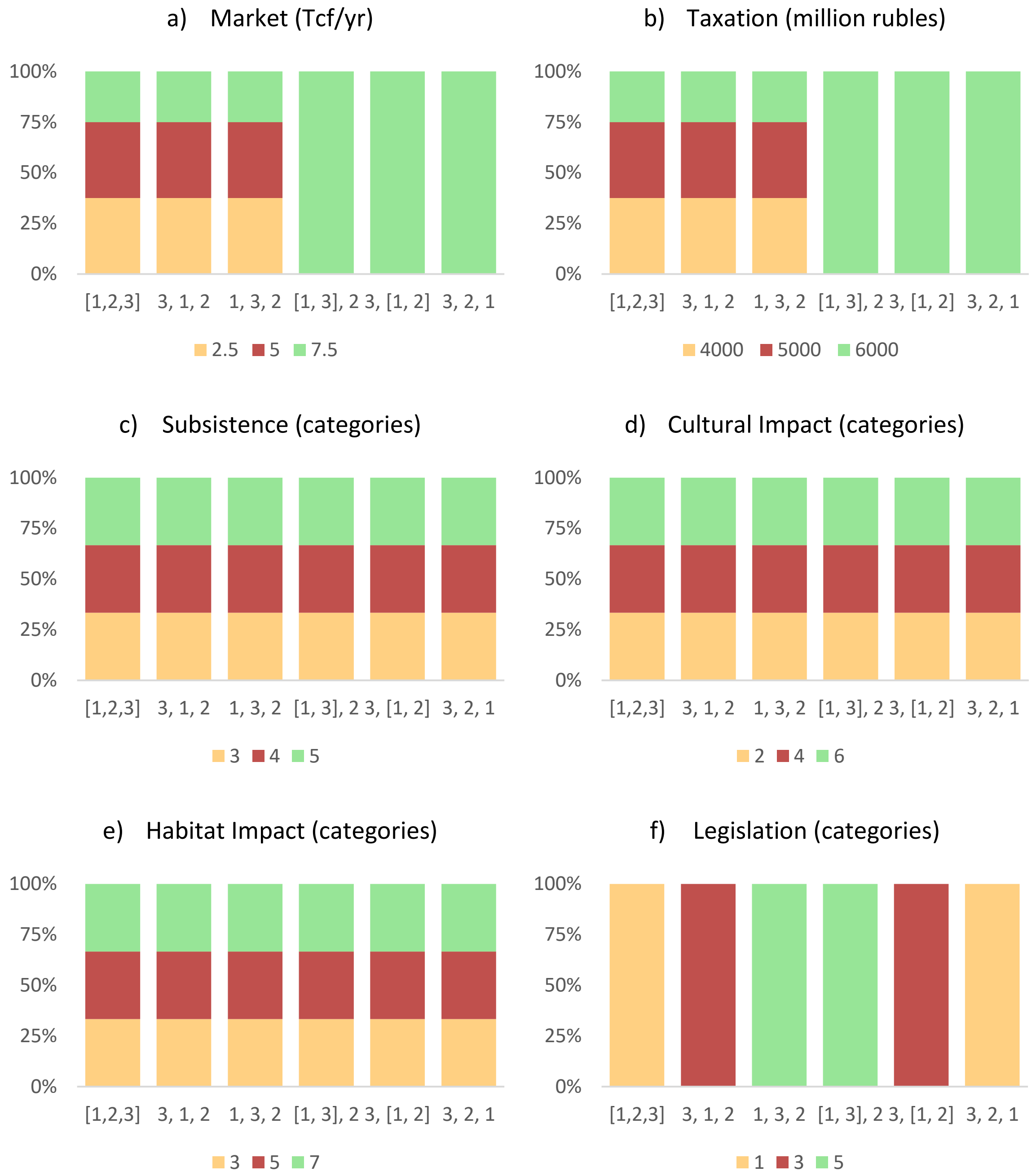


Figure 6.2 *Field production profiles for each alternative.*

Appendix E Messoyakha Veto Threshold Graphs



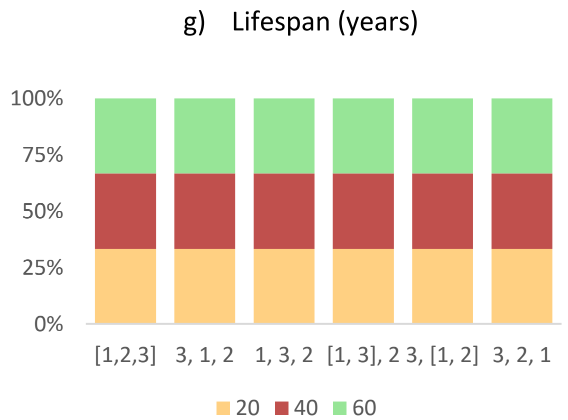
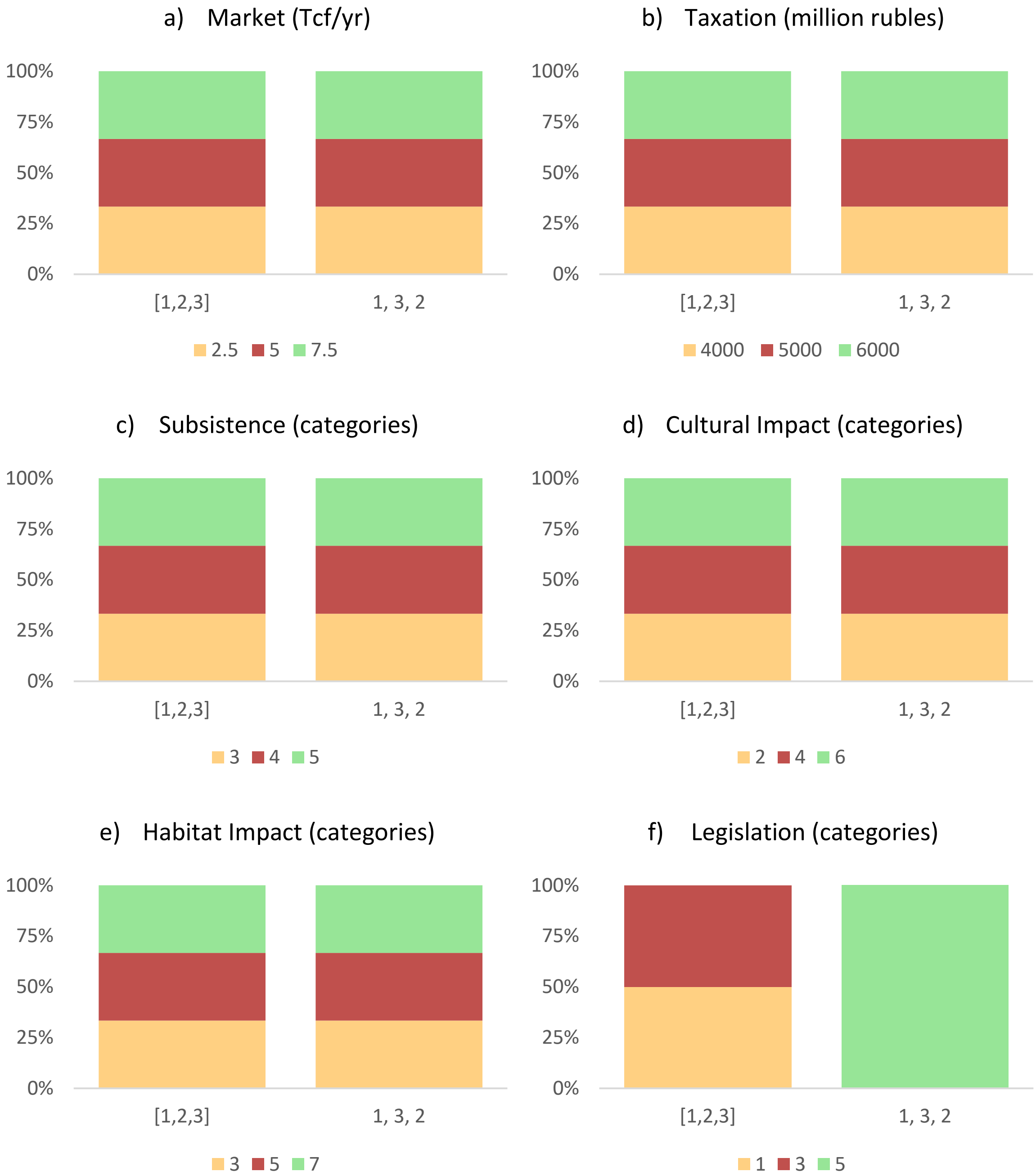


Figure 6.3 *Summary of scenario results with uniform weighting scheme. Each panel shows which veto thresholds lead to each alternative ranking as a percentage of all scenarios.*



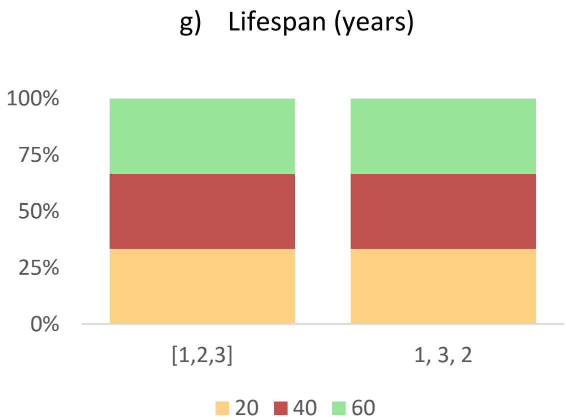
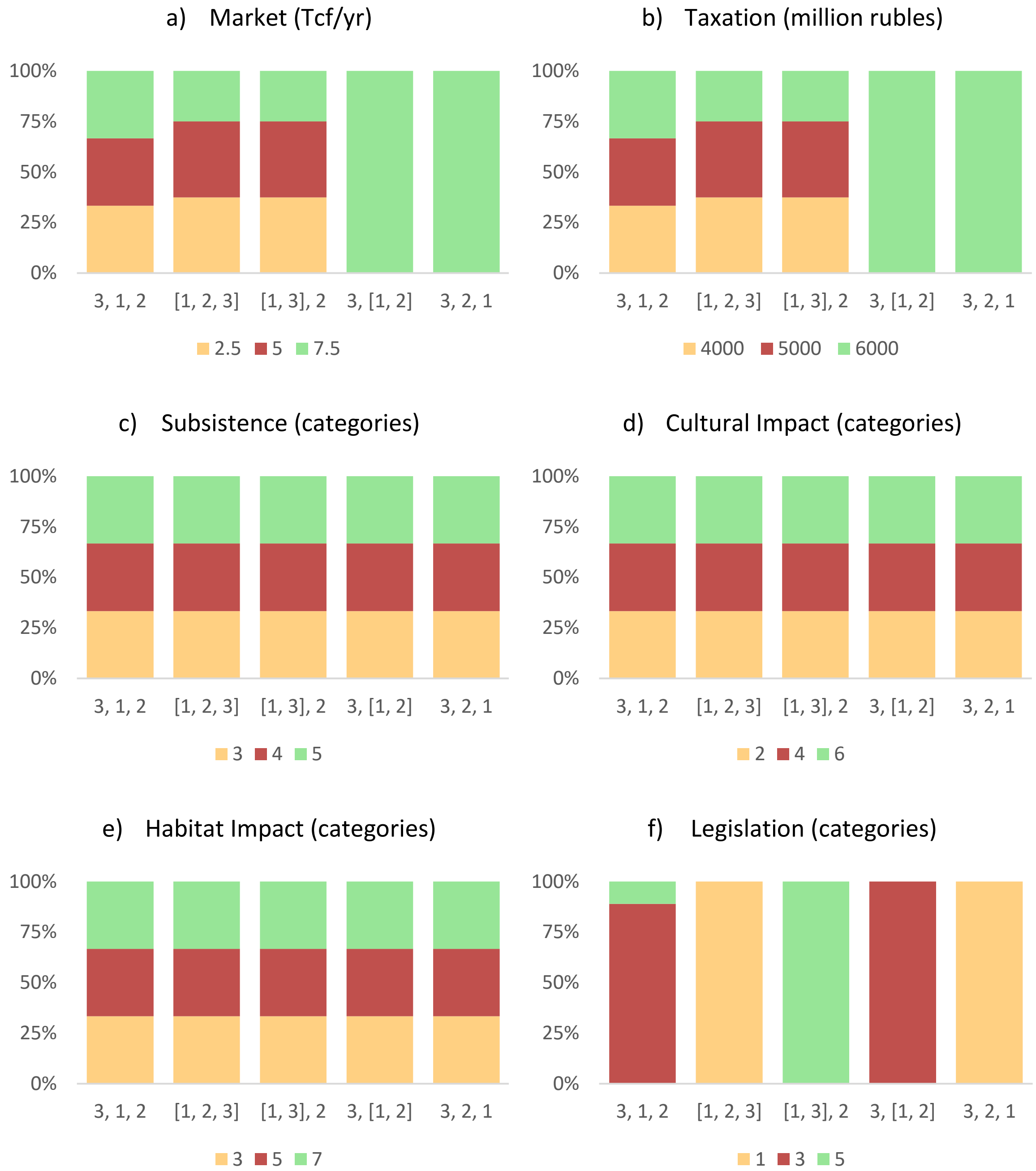


Figure 6.4 *Summary of scenario results with high economic weighting scheme. Each panel shows which veto thresholds lead to each alternative ranking as a percentage of all scenarios.*



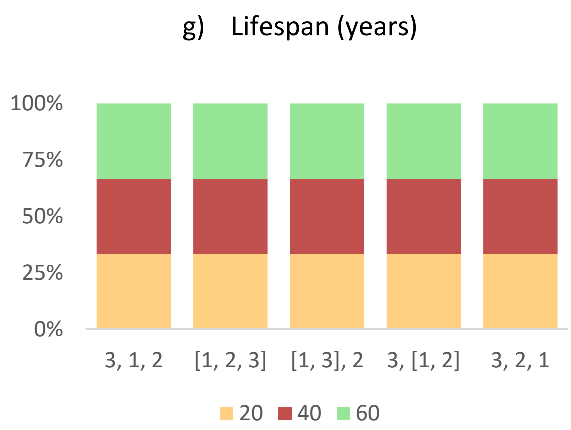


Figure 6.5 *Summary of scenario results with high social and environmental weighting scheme. Each panel shows which veto thresholds lead to each alternative ranking as a percentage of all scenarios.*

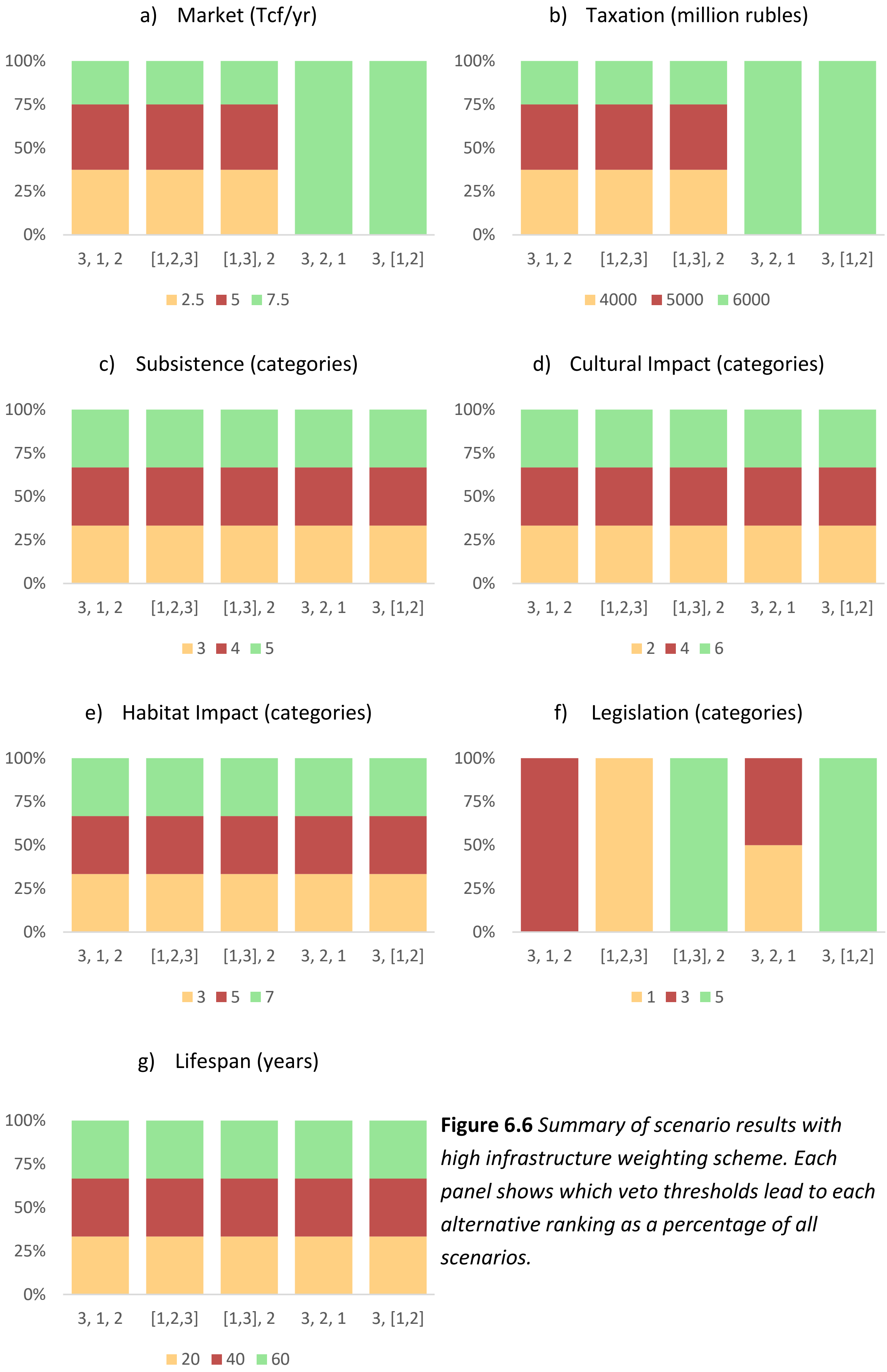


Figure 6.6 *Summary of scenario results with high infrastructure weighting scheme. Each panel shows which veto thresholds lead to each alternative ranking as a percentage of all scenarios.*

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