A social, environmental and economic evaluation protocol for potential gas hydrate exploitation projects

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Abstract

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.

Keywords

Natural gas hydrate; Multi-criteria decision analysis; Decision-making; Energy planning; Alaska; ELECTRE III

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, 2008). 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., 2011). 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.

2. Protocol Development

2.1.1 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., 2016). 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., 2016).

2.1.2 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., 2016). 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., 2016). 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., 2016). 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,…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 the supporting information, Supporting Material S1.

2.2 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 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.

2.2.1 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.

2.2.2 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.

2.2.3 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.

2.2.4 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 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).

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 physical or 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 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 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 2 to evolve over time. Criteria are used to refine the suggested alternatives (Figure 1) by focussing on what can be measured in each proposed alternative.

2.2.5 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 alternatives and M is the number of sub-criteria. 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.

2.2.6 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 1), or contribute insight later in the process through criteria weighting (section 2.2.7). 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 prior to any development (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 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.

2.2.7 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., 2016). 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 the supporting information, Supporting Material S1.

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.

2.2.8 Combination using ELECTRE III and final outputs

The impact matrix is weighted with input from stakeholders and then processed following the ELECTRE III methodology (see Supporting Material S1 for mathematical description of the ELECTRE III method). 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.

3 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.

3.1 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., 2011). 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 3), containing in excess of 1 trillion cubic metres of gas (Collett et al., 2011; 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.

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.

3.2 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 the supporting information, Supporting Material S2.

- *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. 3.3 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 1.

3.4 Case study criteria

From those described in Section 2.3.4, 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 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 1 are given in Supporting Material S2. 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.

3.5 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, LC; indigenous, IC; environmental, ENV; and scientific, 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. 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 (Supporting Information S3) to establish their criteria weights using the revised Simos' procedure. Stakeholders were finally asked ELECTRE specific questions (Supporting Information S3), to establish preference thresholds on these criteria, with the ultimate aim of ranking the four project alternatives for each respondent. The interview protocol adhered to is included within the supporting information, Supporting Material S3. Collected stakeholder responses were anonymised and only attributed to their stakeholder group (IND, GOV, IC, LC, ENV, SCI). Individual stakeholders are referred to individually by a number within these groups (e.g. IND1, IND2, etc.).

4. Results

4.1 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 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 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.

Recreation and aesthetic impact are given lower average weight than all other sub-criteria (Figure 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 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 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 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 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 5).

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 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 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).

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.

4.2 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 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 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.

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 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.

5. Discussion

5.1 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.

5.2 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 1, will allow the completeness of the alternative set to be checked.

5.3 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 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.

5.4 Limitations of the case study example

5.4.1 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 5.2 and 5.3). 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.

5.4.2 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 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 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.

5.4.3 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 a 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 weights 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.

6. Conclusions

6.1 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.

6.2 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.

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Table 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/Yr)*	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

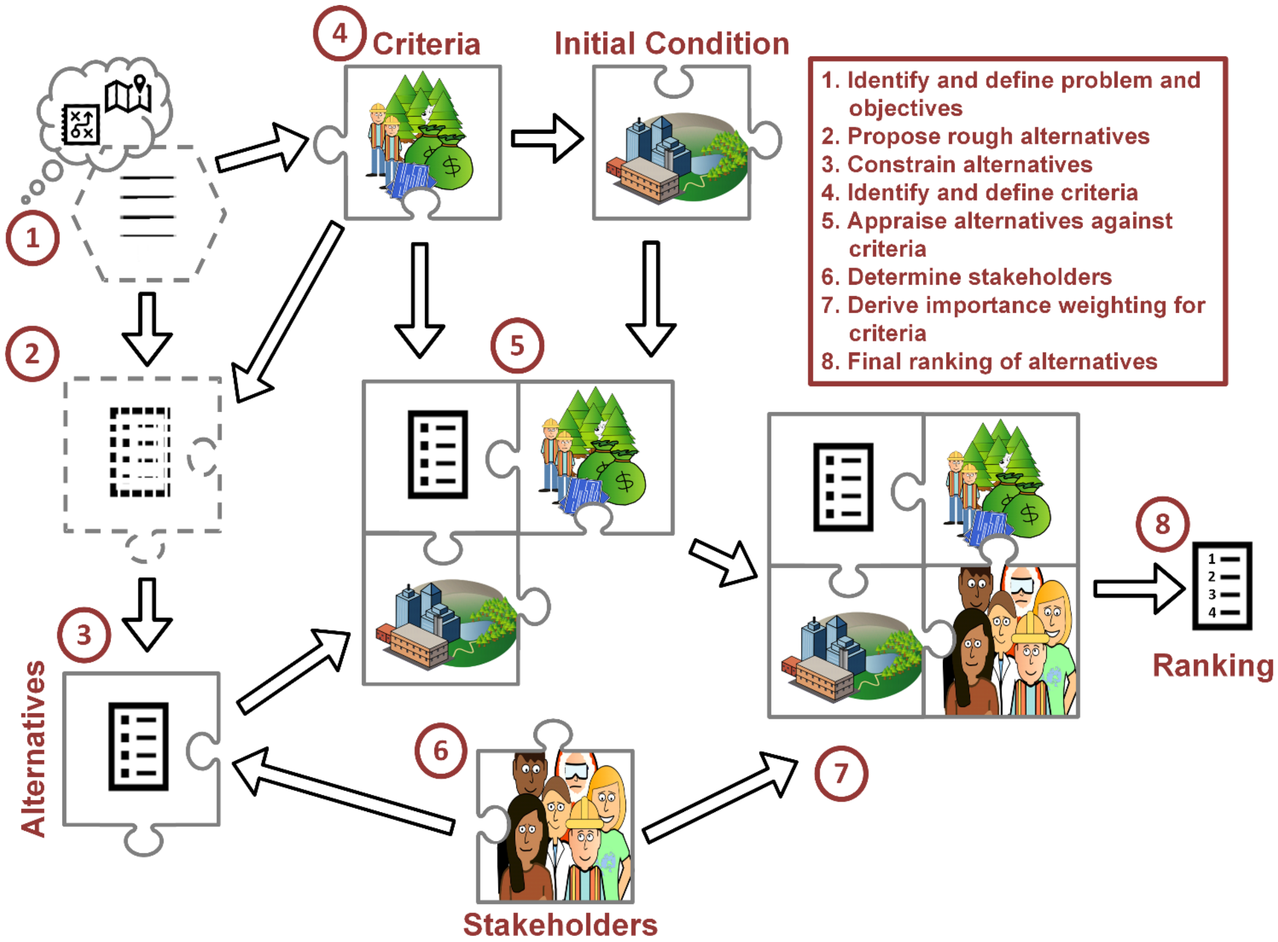

Figure 1: Schematic of protocol steps, links between protocol steps and how each protocol component combines into the final product. Protocol steps are also iterative, and do not have to be followed in the sequence given here, until step 6. Dashed lines for step 1 illustrate the high malleability of 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.

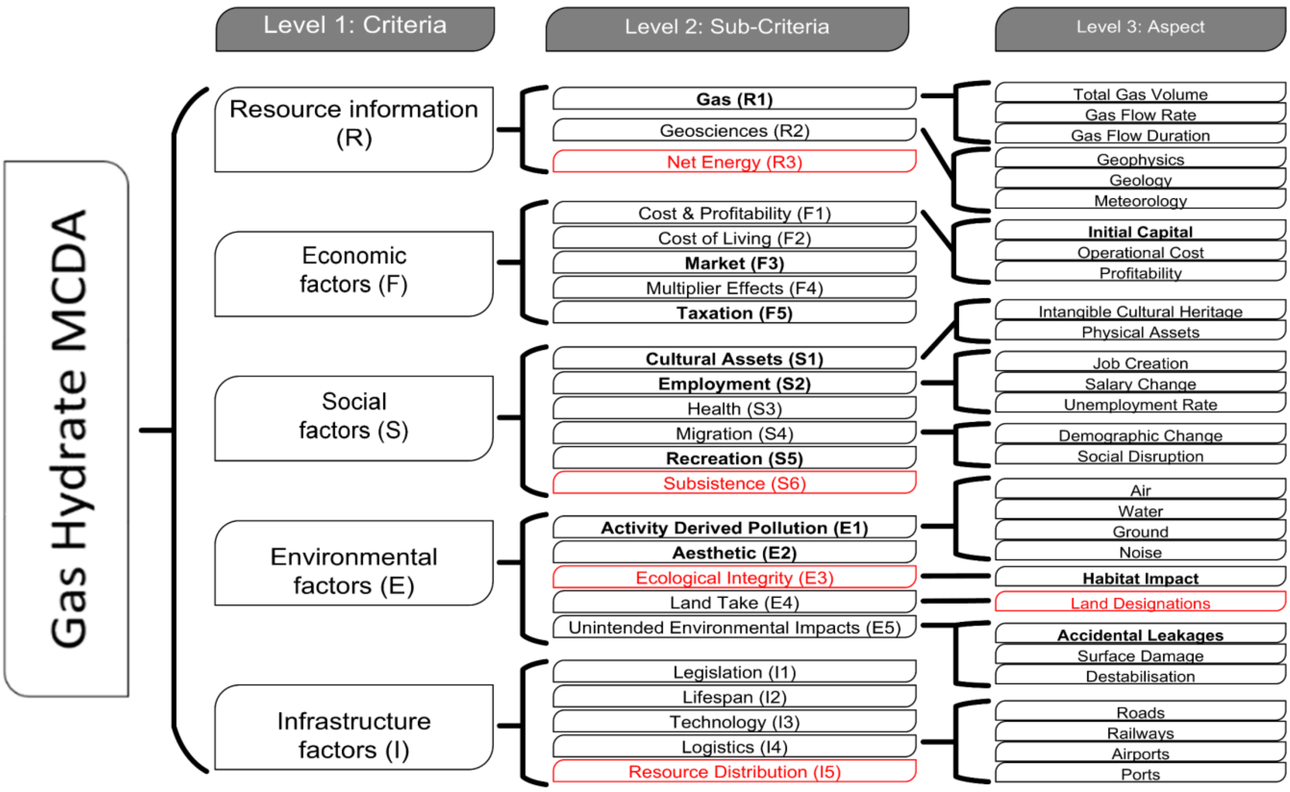

Figure 2: Hierarchy of criteria and sub-criteria, with some potential aspects shown for certain sub-criteria. Criteria and sub-criteria highlighted in black were the full range from which criteria used in Alaska were selected, while red criteria and sub-criteria were suggested during protocol testing in Alaska. Habitat impact originally occupied the position of ecological integrity.

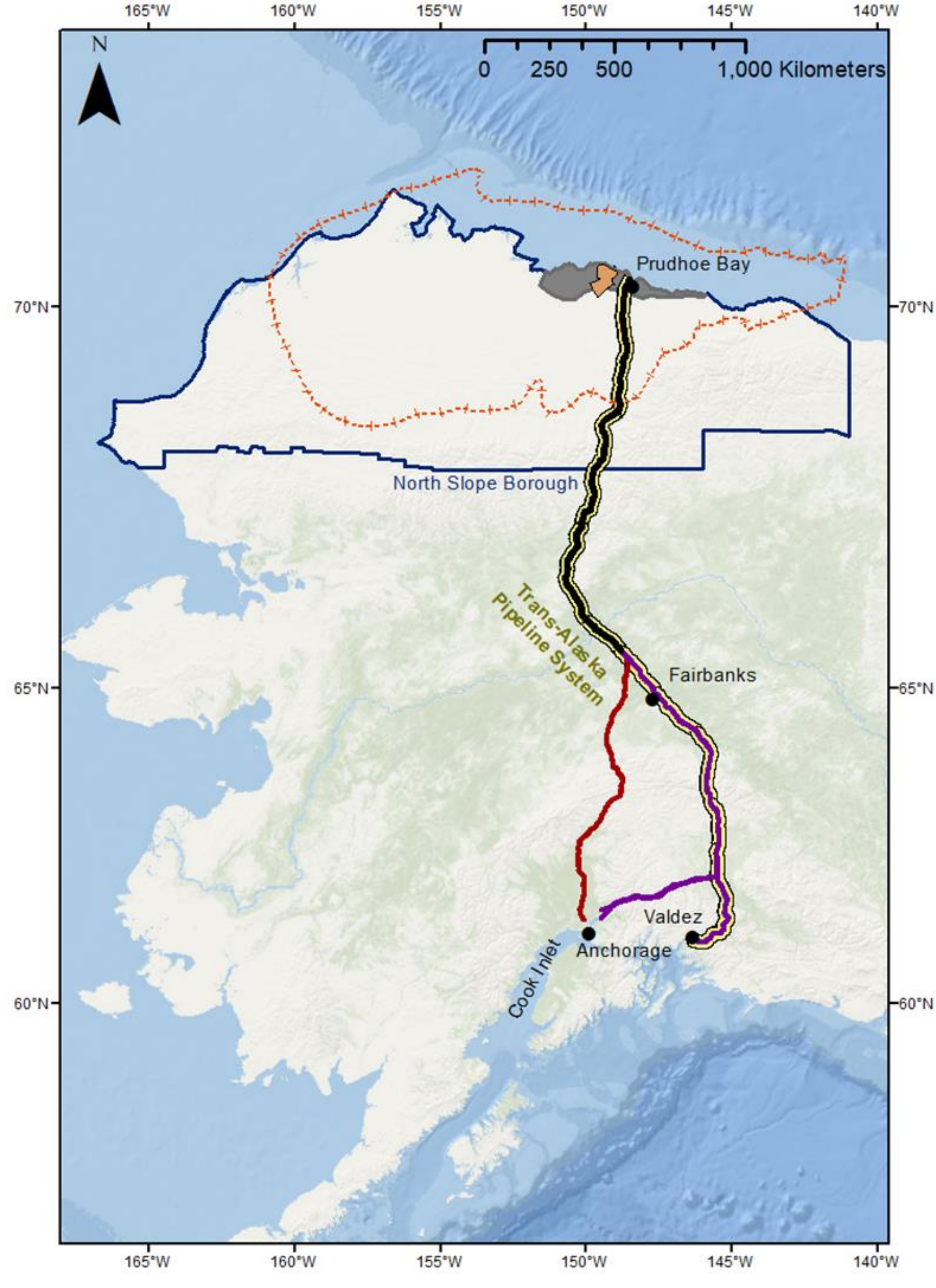

Figure 3: Map of Alaska showing features relevant to our study. The orange region is the Eileen gas hydrate accumulation, which is the area we develop for gas hydrate. The solid grey region is the extent of the area that has currently been developed for conventional oil and gas and the dashed line shows the limit of the North Slope gas hydrate stability zone (Collett et al., 2011). 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.

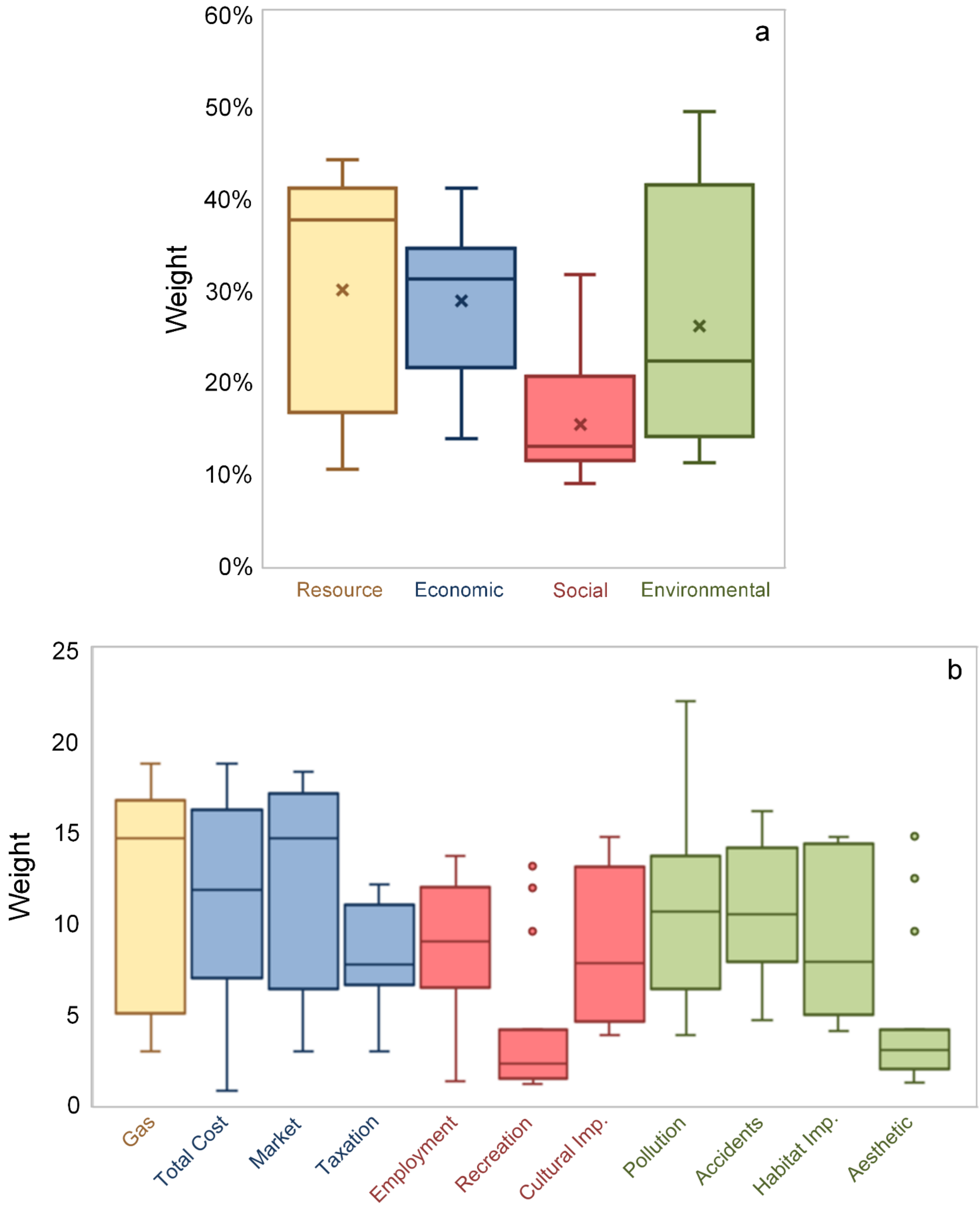

Figure 4: a) Boxplots showing spread of average weight given to the four main criteria across all stakeholders, normalised as a percentage of total weight. Crosses show mean weights for each criterion. b) Boxplot showing range of weights given to each of the 11 criteria by all stakeholders. Circles show 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 or lower quartile.

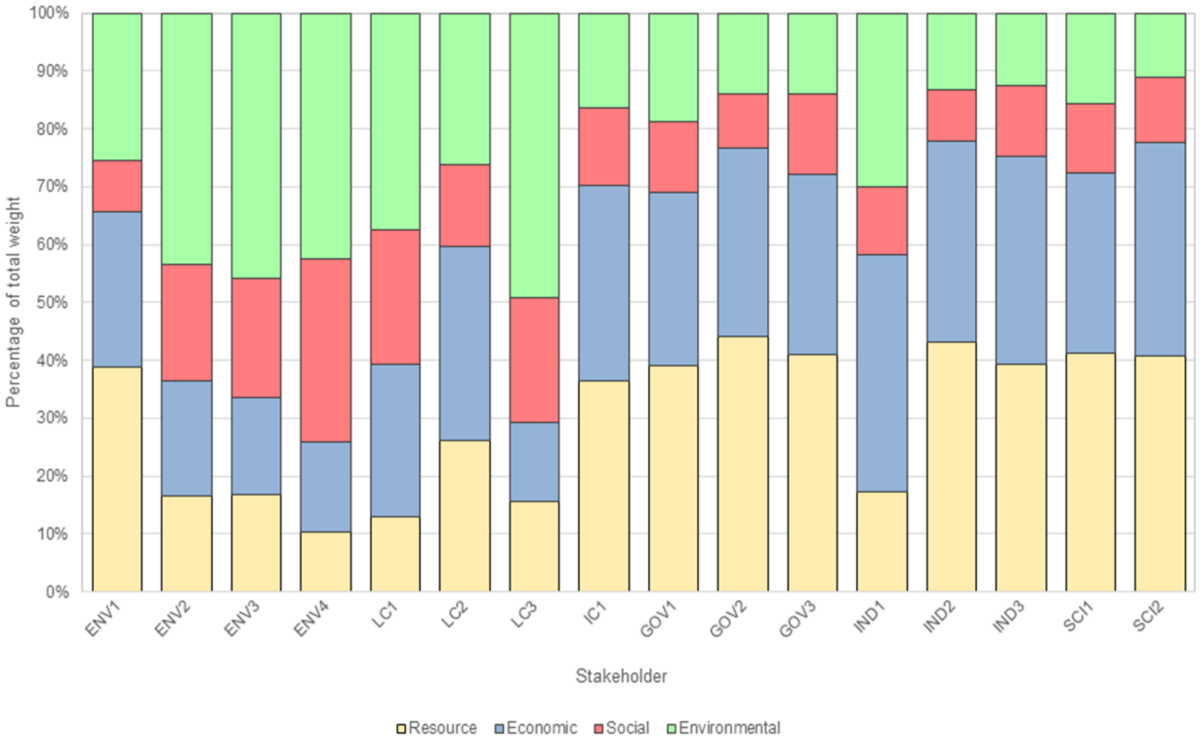

Figure 5: Comparative breakdown of weight given to four main criteria areas by all stakeholders. Results presented as a proportion of total weight normalised to remove effects of different numbers of sub-criteria within each criterion. Stakeholder classification: industry, IND; government, GOV; indigenous community, IC; local community, LC; environmental, ENV; and scientific community, SCI

	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 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.

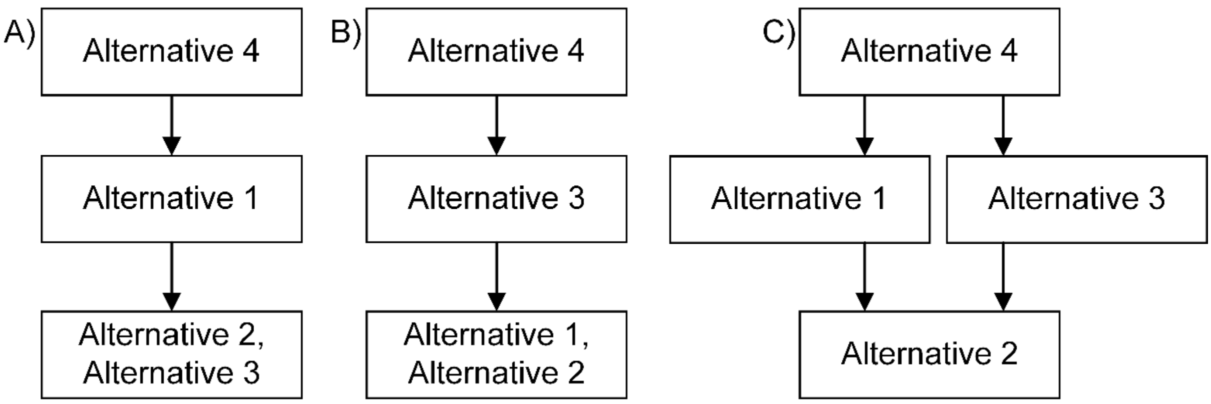

Figure 7: Range of possible rankings of proposed alternatives calculated using ELECTRE III for Alaska stakeholders, with arrows indicating direction of outranking. c) The two unconnected alternatives are calculated as incomparable.