Decision Support for Pathways to Zero-Impact Shipping

About Us

Clear Seas an independent Canadian not-for-profit research centre that provides impartial and fact-based information about marine shipping.

Clear Seas' work focuses on identifying and sharing best practices for safe and sustainable marine shipping, encompassing the human, environmental and economic impacts of the shipping industry.

Clear Seas research and publications are made available at clearseas.org

About this Report

Clear Seas initiated research on the **Pathways to Zero Impact Shipping** project for the purpose of assessing the potential contribution of technology solutions to reducing the impacts of marine shipping across a comprehensive range of environmental impacts. This work generates formal decision support for marine shipping stakeholders facing difficult choices related to technology adoption and innovation. Moreover, through a case study approach, it provides detailed assessments of a set of high impact alternatives.

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Acronyms and Abbreviations

B.C.	British Columbia
CCG	Canadian Coast Guard
DFO	Fisheries and Oceans Canada
DSS	Decision Support System
IMO	International Maritime Organization
km	Kilometres
km^2	Square kilometres
m^3	Cubic metres
MCDA	Multi-Criteria Decision Analysis
NRC	National Research Council of Canada
R&D	Research and Development
SDM	Structured Decision Making
TC	Transport Canada
TRL	Technology Readiness Level

Executive Summary

This report summarizes the work completed by the Pathways to Zero-Impact research project, a collaboration between the University of British Columbia (UBC), Clear Seas, and the National Research Council of Canada (NRC). The project goal was to identify and develop decision support practices and tools for the marine shipping industry to support more holistic consideration of a comprehensive range of environmental impacts for marine technologies and fuels.

In this research project, we examined the decision contexts and decision support needs for two different areas of the marine sector: vessel design and procurement (Canadian Coast Guard, CCG); and research and development (National Research Council of Canada, NRC). We also conducted interviews with professionals from other areas of marine shipping such as industry and consulting. These areas of practice captured through our multi-stakeholder approach are distinct in their decision-making scope, stakeholders involved, and outcomes, but they are united by their role in shaping the technologies and design parameters that will define future vessels.

Throughout this work we observed that the use of formal decision analysis in marine shipping is currently limited, falling short of its potential contributions. Players across various areas of marine shipping are facing high uncertainty around future fuels, shifting demand, changing routes and regulatory change. Their decisions are high stakes, with health and safety, environmental impacts, economic stability, and business feasibility all hanging in the balance. The solutions available involve trade-offs across those domains and many more. These are precisely the types of challenges that decision analysis is intended to resolve.

Consistent with other sectors, across our two case-studies, we observed challenges with decision-making in large organizations, where different groups and actors have different strategic focus areas and responsibilities. Organizational silos can result not only in different prioritization of objectives, but also barriers to more strategic-level analysis for organization-wide goals, when expert and experiential knowledge of specific areas (e.g., operations) and their constraints is held by different actors. Different actors are also often operating with different implicit assumptions about system boundaries and scope (e.g., lifecycle or in-use impacts), the relative importance of objectives, and attitudes towards risk and uncertainty (e.g., how to weigh impact vs. likelihood). These realities underscore the need to invest time in problem structuring before decision-making: arriving at a common understanding of what matters, how it can be measured, and why.

There are a range of tools and techniques to support both problem structuring and decision analysis, of varying levels of complexity. As a result, there is a need to strategically map level of effort to both the potential impact of decision-making (e.g., size of a funding program), urgency, and degree of existing consensus. Matching appropriate strategies to needs of the context may be what is required to bridge the gap between research and practice. Thus, in our decision support framework, we have recommended a structured process for asking questions, identifying needs, and matching them to tools and approaches as part of the structured decision-making approach. Finally, in conditions of high uncertainty, rather than solely focussing on foresight, organizations can also shift to a robustness and resilience-based approach in design. Design for modularity, flexibility, upgradeability can support cycles of acting-learning-updating in marine technology investment.

We hope that this decision support framework and guidance will contribute to the scaling up of decision analysts' attention to marine shipping. There will be challenges: marine shipping is a field in which lived experience is highly important and valued. Any work to formalize decision support must be grounded in that experience both for the quality of outputs and legitimacy. We also recommend merging decision analytic techniques with systems design approaches, as the physical demands on people, vessels and infrastructures across marine shipping routinely cut across multiple socio-ecological systems, making systems thinking a critical aspect of success. We see this project as one step in embedding these values into marine shipping decision support to respond to the unique needs of this critical sector.

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1.0 Introduction

1.1 Background and Context

Marine shipping provides the most energy-efficient option for transporting freight, making it an important lever for reaching global sustainability goals. However, with shipping volumes increasing, concerns are rising regarding the sector's environmental impacts [1]. As such, while providing critical social and economic services, decision-makers in marine shipping are increasingly tasked with meeting evolving and often competing targets related to environmental performance [1]. Selecting vessel technologies that can reduce negative environmental impacts is one important way to work towards a more sustainable sector. However, while vessels interact in complex ways with the ecological and social systems through which they transit, siloed decision-making means that the environmental performance of vessels is routinely addressed focusing on single indicators that do not adequately capture the complexities of vessel's socio-environmental impacts [2]. For example, one technology for reducing vessel sulfur emissions, known as scrubbers, has raised concern from port cities because scrubber use can increase water contamination. As such, adopting scrubbers meets regulatory performance measures for one environmental objective, but fails to reduce overall environmental impacts [3], [4], [5]. This raises a central challenge – how to evaluate alternative pathways for marine shipping without neglecting important trade-offs and co-benefits across a suite of socio-environmental impacts.

Innovation for reducing the environmental impacts of vessels is a complicated task. For example, the purpose of a vessel greatly impacts the innovation space available in terms of technology feasibility and risk aversion. Environmental considerations can, at times, compete with critical vessel requirements (i.e. electrifying a search and rescue vessel may impose challenging trade-offs in terms of limiting the ability to respond to emergencies while a vessel is charging) or be complementary (i.e. co-benefits between cost and emissions improvements from energy efficiency). Reducing the environmental impacts of vessels while meeting seemingly intractable objectives with limited resources is the difficult landscape in which marine shipping professionals operate.

This project responds to these types of challenges by integrating best practices from systems theory and structured decision-making. Systems theory provides tools for understanding and managing the systemic nature of risks, opportunities and interconnectedness between design options and the broader context in which ships operate. Structured decision-making provides auditable methods for articulating and evaluating the observations gleaned from systems modeling and aligning the perspectives of multiple stakeholders in decision processes that minimize the impacts of hidden decision traps and bias's [6], [7], [8], [9]. Herein, we provide a report of research activities at the Pathways to Zero Impact Shipping project and an adaptable decision support framework for marine shipping professionals, with guidance on implementation.

1.2 Purpose and Outcomes of the Study

The Pathways to Zero Impact Shipping research project, a collaboration between the National Research Council of Canada (NRC), the University of British Columbia, and Clear Seas, is funded by the NRC and Mitacs Accelerate Program. This project develops an evaluative framework that is fit-for-purpose for marine shipping stakeholders assessing the comprehensive environmental impacts of marine technologies and fuels, draws on best practices from the decision sciences and is supported by tools for a systems-based approach to evaluation. We worked closely with stakeholders to co-develop and pilot a process for evaluating alternative technological pathways for marine shipping that captures a comprehensive suite of environmental criteria. This contribution will assist stakeholders in the marine shipping sector in avoiding unanticipated outcomes, strategic surprises, ignored trade-offs and co-benefits, and 'better-before-worse' outcomes over time, instead supporting future-oriented and defendable decision-making.

2.0 Maritime Shipping Decision-Making: Context and rationale for case studies

While decision-making always boils down to selecting a given solution from a set of alternatives, how to go about the evaluative process is affected by the situations' environment. That environment is defined by four main factors: the level of uncertainty in the decision situation, how completely and quantitatively the benefits and costs of the alternatives can be assessed, if the decision addresses the achievement of a single or multiple objectives, and how many participants have power over the choice[10]. The maritime shipping sector involves decisions that vary on all these dimensions, at different arenas and scales, and they interact with one another. To manage this complexity while still capturing decision challenges that are transferrable across the sector, we implemented one scoping study and two case studies.

Our scoping study, presented separately in the **Ship Design and Technologies to Reduce Environmental Impact** report, shed light on how decisions are made by industry players and what promotes or inhibits their adoption of green technologies [11]. We interviewed industry professionals across a variety of roles in maritime shipping, capturing considerations around regulatory compliance, design optimization, procurement and service delivery. This allowed us to get a broad picture of the challenges the sector faces in decision-making and the techniques they used to make those choices. From these interviews we documented informational needs ranging from the quantitative (e.g. capital costs, emissions estimates) to the qualitative (e.g. familiarity with a technology or design feature, other industry trends). We found that vessel design decisions are difficult to generalize being sensitive to an array of considerations (e.g. vessel type, purpose, life-stage, and market and government forces), but that quality-trusted performance data, regulatory certainty, and government support for innovation and pilot projects are gaps that could support the adoption of innovative environmentally responsible technologies [11].

We then conducted two case studies that, while united in the shared goal of reducing the environmental impacts of vessels, represented qualitatively different decision contexts (**Table 1**).

Table 1: Decision environment for Canadian Coast Guard (CCG) and National Research Council, Canada (NRC) case studies

Decision Attributes	Canadian Coast Guard Case Study	National Research Council Case Study
Uncertainty	Varied – low to high	High
Data Type	Quantitative, some qualitative	Qualitative, some quantitative
Objectives	Multiple	Multiple
Participants	Multiple	Single or Multiple
Foresight	Short to medium term	Long term
Focus	Optimizing across multiple objectives	Supporting informational needs and shaping future opportunities
Scope	Fleet and vessel choices	System/sectoral
Constraints	Hard/defined	Exploratory
Decision Level	Tactical – operationalization and implementation	Strategic – vision and direction

2.1 Case Study 1: Reducing the environmental impacts of Canada's Coast Guard Fleet of Program Ice Breakers

Note: During this research project, the Canadian Coast Guard was a special operating agency within the Department of Fisheries and Oceans. During the final year of the project CCG moved to the Department of National Defence, a change announced on June 9, 2025 that became effective as of September 2, 2025 [12] . Our description of the CCG mandate and role will be reflective of its status prior to the change as our case study data collection was conducted prior to June 9, 2025.

The Canadian Coast Guard operates Canada's civilian fleet on all three of Canada's coasts, with a mandate of supporting the safety of the marine environment and mariners and supporting economic trade by ensuring safe and efficient navigation within Canadian waters. CCG supports and maintains critical maritime services including aids to navigation, marine communications and traffic services, icebreaking and ice management, channel maintenance, maritime search and rescue, response to marine pollution and hazardous vessels, providing helicopters for other federal departments when needed, supporting scientific and navigational surveys. They maintain a fleet of vessels including large and small vessels, motor lifeboats, air cushion vehicles and helicopters as well as shore assets such as communications sites and aids to navigation [13]. At the time of this study, they were engaged in fleet renewal with an emphasis on ice breaking capacity.

For our case study we engaged with CCG professionals engaged in policy, ship procurement, design, and engineering, surfacing considerations and debate around **technology adoption for program ice breakers**. As such, we characterized thinking around a design-centric, near-mid-term timeline (i.e. a mid-life upgrade within the next 5-10 years, for a vessel with 50 year lifetime,), tactical level of decision-making that aims to optimize design within a set of bounded constraints (e.g. requirements of the national shipbuilding strategy, regulations, performance requirements).

2.2 Case Study 2: Identifying priorities for Canadian research and development for a future-ready maritime fleet with the National Research Council of Canada

Our second case study was conducted with the National Research Council, Canada: Ocean program, a federal research and development (R&D) platform supporting collaborative research towards a sustainable Canadian blue economy [14]. The Ocean program funds collaborative work involving industry, academia, Indigenous organizations and government to advance emerging and innovative technologies.

The ocean program is tasked with prioritizing competing proposals that are often incommensurable because they address widely different research areas such as decarbonizing vessels and nature-based solutions to protecting coastal areas. Our case study focused on how to **support decision-making around evaluating research and development alternatives** through the co-development and testing of a comprehensive set of key performance criteria. Compared to vessel design considerations, this is a more strategic level question about how to measure the potential of competing research pathways to positively shape the opportunities for reducing the environmental impacts to Canada's maritime and coastal environments, over the long term.

2.3 Capturing breadth and depth through case diversity: Case study methods

These two case studies are connected. Improved understanding and communication of the needs of decision-makers at the tactical level informs the longer-term strategic goals for R&D. Moreover, by considering these two case studies, we identify a broad range of decision support needs in the maritime industry, grounded in realistic challenges.

Our research workflow (**Figure 1**) was designed to prioritize early and frequent collaboration with intended end users of the decision support framework, a best practice in decision support design generally [15] and structured decision making specifically [7]. As such, our engagement with case study partners began prior to identifying a case study topic.

First, we began a literature review of environmental impacts of maritime shipping and vessel technologies. With the literature review ongoing, we began interviews with our case study partners, the CCG and NRC. These expert interviews were broad ranging, serving to inform the development of case study topics and provide contextual expertise around each institution and the members' perspectives on maritime shipping, environmental impacts, priorities, challenges and opportunities facing the sector. We drew on findings from the interviews and follow-up queries to identify case studies of interest to our partners as well as for which we had sufficient data and expertise to engage meaningfully. We then designed and delivered structured decision-making workshops tailored for each case study.

We conducted a series of participatory workshops for each case, tailored for the participating partner (CCG or NRC). For both organizations, the first workshop targeted the problem structuring phase of decision-making; however, they were delivered using different tools. The CCG workshop was delivered using an in-person/hybrid format and the NRC workshop 1 was entirely online. Following each workshop 1, the UBC research team conducted in-house analyses to fill in data gaps, develop evaluative frameworks around the focal issues, and identify or develop tools needed to conduct our second set of structured decision-making workshops. We then conducted a second workshop for each case study which targeted preference elicitation and tested multi-criteria tools we had identified and developed. Data from workshop 2 consisted of transcripts of facilitated discussions and outputs of interactive tools used to record assessments. The UBC team then analyzed that data, the findings of which are summarized in separate reports. Finally, we synthesized our observations around decision support for maritime shipping pathways to zero impacts in this final report.

Figure 1: Generalized Research Workflow

3.0 Key Components for Supporting Decision-making for Sustainable Marine Shipping

In this section, we summarize our collected insights from two case studies in marine shipping decision-support, highlighting critical components of formal support for reducing the environmental impacts of the marine shipping sector. We summarize both general recommendations for approaches to take and review specific techniques and technologies that are available to operationalize those approaches. There are many ways to implement and adapt structured decision-making and we summarize specific tools we have implemented and tested in this project.

3.1.1 Pathways to Zero Impact Decision Support Framework

Decision Support Systems (DSS) refer to a range of interventions to facilitate informed, reasoned, and auditable decisions in complex situations. These range from the involvement of external experts in decision-making, analytic techniques that may or may not be operationalized in software programs, process management, systematic best practices, and a range of computerized tools [16]. Our framework (**Figure 2**) includes a systematic guide for integrating best practices from decision analysis, recommendations for approaches to elicitation and decision analysis that align with the marine shipping decision context including examples of specific tools we tested in two case studies, and novel analytic support we develop in response to decision support capacity gaps identified during our case studies.

Responding to initial scoping (literature review and expert elicitation), our decision support framework emphasizes techniques developed for systems analysis [17], [18], [19] and structured decision-making (SDM) [7], [8], [9]. Systems approaches are needed to capture the interdependent and interconnected nature of marine shipping, without which an understanding of causality and consequences will be inadequate to the task of comprehensive evaluations. Structured decision-making provides a systematic approach to identifying and communicating decision goals, generating alternatives, eliciting expertise, evaluating trade-offs and avoiding common errors in human and group judgments such as alternative-based thinking, bias and groupthink [6].

Our framework outlines steps for adapting structured decision-making to marine shipping contexts. We test and evaluate existing decision support tools for eliciting and analyzing expert knowledge in group decision-making, handling different data types and visualizing and communicating information.

Decision Opportunity

May be initiated externally or internally
May be proactively created

(1) Clarify the Decision Context

Questions to resolve

- Do I understand the decision?
- Does my team have a shared understanding of the decision?
- Do we agree that this is the right decision to solve?
- Is this a long term (strategic), short term or urgent decision?
- Who can make the decision?
- What do they need to make the decision?
- When does the decision need to be made?

Potential Methods and Tools

- Scoping reviews
- Expert, stakeholder, and decision-maker interviews
- Systems modelling (e.g., strategy mapping)

What we did

- Literature review
- 23 expert interviews and collaboration to identify case study focal decisions

(2) Define what you are aiming to achieve and how you will measure achievement

Questions to resolve

- What are our goals and how can they be structured and organized?
- What are appropriate performance measures?

No / Yes

- Does the decision as it is framed align with achieving the goals identified?

Potential Methods and Tools

- Stakeholder and expert elicitation to identify goals (through interviews, structured workshops — online or in-person)
  - *In-person strategies:* Must/Can't/ Preferred elicitation followed by facilitated query-based group discussion
  - *Online strategies:* strategy-mapping, collaborative modelling, facilitate small-group expert discussions
- Expert elicitation to identify performance measures

What we did

- Structured decision-making workshops and strategy mapping
- Produced preliminary goals and performance indicators sourced from literature and also through development of new scales

(3) Identify a set of alternatives

Questions to resolve

- Are there externally defined alternatives that are relevant to the decision?
- Are alternatives able to be designed as part of this process?

No / Yes

- Are the defined performance measures relevant to the alternatives being considered?

Potential Methods and Tools

- Literature review
- Expert elicitation
- Collaborative processes
- Alternatives may be pre-defined

What we did

- *Coast Guard:* alternatives identified from workshops, expert elicitation and academic and industry literature
- *National Research Council:* study team generated hypothetical alternatives that capture a range of attributes in terms of range of impacts, scale of impact, and likelihood

(4) Estimate the consequences of each alternative over the set of performance measures

Questions to resolve	Potential Methods and Tools	What we did
• How does each alternative perform against each objective, as captured through selected performance measures? • How uncertain are these estimates of potential consequences? • What trade-offs or co-benefits exist for each alternative across goals?	• Estimation of consequences through: expert judgments, literature review, direct measurements, simulation • Systems modelling to capture interdependencies between objectives - *Strategy mapping* - *Cross-impact balances analysis* • Scenario building to generate a holistic view of cascading impacts of alternatives	• *Coast Guard:* tested CIB analysis, literature review and novel analysis for selected objectives (e.g., supply chain vulnerability) • *National Research Council:* decision-makers assessed alternatives against objectives using expert judgment

(5) Determine weights/prioritization for full set of goals

Questions to resolve	Potential Methods and Tools	What we did
• What is the importance of each objective, relative to others? • How should uncertainty in performance be taken into account (e.g., how to weight best case vs. worst case)?	• Expert and stakeholder elicitation to determine preferences and weight goals • Group facilitated elicitation (in-person or online) • Range of techniques available including: option prioritization, rating, ranking etc. Examples of computerized support: StrategyFinger, GMCR+, Altaviz, spreadsheets	• *Coast Guard:* Altaviz decision support platform to support direct ranking, swing weighting • *National Research Council:* Excel-based spreadsheet to support direct ranking, weighting

(6) Select alternative or generate novel strategy based on insights from analysis

Questions to resolve	Potential Methods and Tools	What we did
• What alternatives (if any) achieve the most important objectives we hold? • How are these alternatives ranked overall? • If there is no winner - do we need to return to an earlier step to refine our analysis or seek more alternatives? • How can we best protect what is highly valued to those impacted by this decision - are there any win/wins?	• Multi-criteria decision analysis methods such as analytic hierarchy process, simple weighted scoring (sum or product), reference point methods	• *Coast Guard:* direct ranking, weighted sum • *National Research Council:* direct ranking, weighted sum

Figure 2: Decision Support Framework developed through Pathways to Zero Impacts project

We envision our framework beginning with the appearance of a decision opportunity, although, for a given choice and decision-maker, the process may begin at any stage. For example, a set of alternatives may be pre-defined, with little room for change. However, even in such situations, we recommend considering the elements in step 1, to ensure that opportunities for improving the decision framing or seeking to generate overlooked alternatives are not missed. Our aim is to provide a prescriptive but adaptable map to sound decision-making that is grounded in decision theory and fit-for purpose for the marine shipping sector.

The subsequent sections describe step-by-step practices for each of the six steps outlined in the decision support process (**Figure 2**), recommendations for using existing tools (e.g. Strategy mapping, CIB analysis) for implementation, sample forms, activities, consequence tables and matrices as developed for this research, and data related to any novel software developed to facilitate computerized decision support, as piloted through the two case studies. Drawing on the NRC and CCG case studies, documentation in the framework provide real-world examples of the tools and techniques included and guidance for implementation across different types of decision contexts.

3.2 Decision Analytic and Systems Approaches Used to Implement the Framework

3.2.1 Structured Decision-Making

Structured decision-making (SDM) is a flexible formalized approach to group decision-making for complex situations [20]. Particular attention is paid to problem definition and identifying, defining and organizing objectives and performance measures. SDM is flexible, with specific steps varying based on the problem at hand. We have employed a range of techniques within each case study to reflect the best practices of SDM while responding to the unique characteristics of each decision context. For example, in the CCG case study, some of our participants were able to participate in our first workshop in-person and some participants joined us online. We developed an SDM activity that was interactive in-person with physical boards and sticky notes used to collect insights. We made this activity accessible to online contributors through an online chat and proxy facilitators who filled out physical notes on behalf of online contributors.

To accommodate budgetary constraints and scheduling difficulties, we took a different approach to workshops with the NRC. Instead of one in-person/online hybrid workshop, our first group expert elicitation activity was conducted in a series of small online mini-workshops with one larger workshop at the end. These workshops still followed structured decision-making practices, but instead of in-person activities, a facilitator guided participants in using *Strategyfinder* software, a decision support software tool to help teams working remotely to collaborate in complex decision-making. *Strategyfinder* is described in more detail in section 3.2.2. In both case studies, our first series of workshops elicited from experts' decision critical information, key objectives and concerns, and performance indicators which UBC researchers then used to conduct preliminary assessments of technologies (for CCG case study) and key performance indicators (for NRC study), and to develop for both case studies preference elicitation workshop activities. The differing approaches to problem structuring and eliciting objectives and performance indicators provide an example of the range of ways that SDM can be implemented to meet the needs of different organizations and decision-making stages.

We continued to implement SDM in a second series of workshops for each case study. For the CCG case study, we designed and hosted an online preferences elicitation workshop using an existing multi-criteria decision support software system, Alta Viz, developed by Vancouver-based consultancy, Compass Resources Management. In the NRC workshop we mirrored many of the steps and discussion questions followed for the CCG final workshop. However, instead of using Alta-viz software, we used a simple set of spreadsheet tools in an excel-based format for visualization and interaction. By engaging in a similar SDM process using both Atla-viz and excel formats, we highlight the flexibility of structured decision-making.

3.2.2 Strategyfinder Group Modeling Software

To deliver a series of structured decision-making workshops online in the NRC case study, we employed an online strategy mapping exercise facilitated using the Strategyfinder software (https://www.strategyfinder.com/). Using Strategyfinder, participants can collaborate in producing a cause map (a cognitive map collaboratively made by more than one person) of a decision or circumstance and use a range of visualization and analytic tools to explore and discuss system behaviors and consequences. The maps produced are similar to 'cognitive maps', but are distinguished by their group orientation [21]. A facilitator guides the workshop group in providing input with valid causal relationships, in viewing aspects of the maps through real-time analysis and prompting reflection and debate that are documented by adding to or altering the maps in real-time [21]. We anticipated that this software would be particularly useful for implementing structured decision-making because of its ease-of use for workshop participants and its useful analytic and visualization features that can be implemented in real-time during the workshop. Of particular interest are the various loop check analyses which can be used to identify virtuous and vicious cycles, actions that are highly influential to the achievement of identified goals and the identification of elements in the map that lack outgoing arrows (heads) and are hypothesized ends objectives, and tails, which lack incoming arrows but have outgoing arrows and are interpreted as expressing means objectives [22], [23]. Through interactive model development, these tools were used to structure small group conversations around valuable contributions of existing projects to the Ocean Project and to consider how they may be operationalized as criteria in a formalized decision framework.

3.2.3 Scenario Building: Cross Impact Balances

We analyzed a subset of data from the CCG case study using the Cross-Impact Balances Method. Cross Impact Balances is a scenario building method well-suited to complex systems and weakly structured problems. By this we mean problems for which quantitative data is unavailable or inappropriate, where qualitative considerations cannot be translated into mathematical formulae and where the interactions are too complex to be grasped intuitively.

Cross Impact Balances supports the application of expert judgments to create abstract visualizations of complex systems and generate a reasonable set of possible future scenarios for that system [24], [25]. Based on a matrix representation of system elements, the CIB algorithm defines scenarios for which self-reinforcing pressures are consistent [24], generating a realistic set of scenarios that includes future states that may otherwise be missed when intuitively generated without formal support [26]. CIB was chosen because it can handle both qualitative and quantitative data, has informational requirements that can be readily met with input from structured decision-making workshops and is supported by a decision support system Scenario Wizard (https://www.cross-impact.org/english/CIB_e_ScW.htm).

3.2.4 Alta Viz Software for Structured Decision-Making

Alta Viz is an interactive software program that operationalizes structured decision-making, guiding users through its steps with sequential, interactive modules. Using Alta Viz, facilitators can organize decision-relevant information, beginning with problem structuring through to evaluation of trade-offs. Generally, the modules through which participants are guided include decision context, objectives, alternatives, consequences and trade-offs. The included modules summarize findings from in-depth problem structuring; they do not replace those activities. For example, we conducted extensive interviews, literature review and a workshop to determine the content to include in the modules. We then conducted analysis to fill in data gaps that allowed us to generate a consequences table. While much of the material is preset in the software, it is not static. For example, easy to use editing tools allow facilitators to update information as workshop discussions surface new perspectives and the consequences table used to evaluate trade-offs is highly interactive, enabling exploration. Finally, new data can be generated using preference elicitation tools included within Alta Viz. The easy-to use interface and interactive tools allow users to generate and record discussions with multiple stakeholders, focused on a wide range of objectives, judgments of consequences that are auditable in real-time, and trade-offs. Moreover, two distinct methods of preference elicitation (direct ranking and swing weighting) allow for deep examination of preferences. Alta Viz was developed by Compass Resource Management, a Canadian Consultancy in Vancouver, British Columbia.

3.3 Insights on Decision Support for Marine Shipping

Structured Decision-Making can be implemented with a range of techniques. It is sufficiently versatile to provide a foundation for decision support in the maritime sector. We conducted two parallel structured decision-making processes with very distinct stakeholder groups. While both processes were based on structured decision-making (SDM) approaches—a flexible formalized approach to group decision-making for complex situations—they were implemented in different ways in each case study. In-person/hybrid events enabled communication among larger groups and real-time validation of outputs. Online workshops reduced time and budgetary costs. A variety of software programs are available to enhance online group decision support, we tested *Strategyfinder* and *Alta Viz* and developed and tested an *Excel* based platform.

Available decision support systems have different strengths. Consider functional needs as well as technological comfort of anticipated users when choosing an approach. While we found several technologies useful for structuring discussions and recording insights there is always a learning curve with online decision support and time must be taken to familiarize participants with how to use the software functions. Overall, we found that participants caught on quickly with each of these programs and were able to complete all tasks in the workshop. When user-interface problems arose, it was critical to have a facilitator available to guide participants or to input perspectives as a proxy to ensure that everyone could participate.

Among the tools that we explored in the two case studies, *Strategyfinder* was particularly well suited to promoting systems thinking and exploring objectives and the means to reach them. *Alta-viz* and our in-house *Excel* based tool provided visualizations for storing and exploring quantitative and qualitative judgments. All of the programs provided tools for exploring and eliciting preferences and were useful in structuring discussions. *Strategyfinder* was most useful in structuring discussions around interconnections and causality while *Alta-viz* and our in-house software were strong in facilitating discussions around trade-offs. Our early use of Cross-Impacts Balances modeling was not continued into the workshop phases as, while it is computationally advanced and performs well for complex systems analysis, it was not sufficiently user friendly for the case studies at that time.

Digital Security is an important consideration in decision support choice. While commercial decision support systems can have benefits in terms of design sophistication and user friendliness, they may also store data outside of Canada which may be a concern for some stakeholders. This concern was raised regarding our use of *Alta-viz* at a time when tensions between the Canadian and US governments were high. *Alta-viz* was developed and is owned by a Vancouver consultancy, but it does use American servers. While our workshop was focused on hypothetical judgments using publicly available information, that will not always be the case in real-world decision-making and local hosting should be considered. Our development of the *Excel* based system for the NRC workshop is an example of one way to resolve such concerns with only a moderate impact to usability and functionality. Further research into decision support system development with a mind to National Security in a Canadian context will be critical to scaling up a role for decision support in Canada's marine shipping sector.

Formalized decision support is not routinely and comprehensively used in marine shipping decision-making, with some exceptions. We suggest that the high uncertainty and high stakes nature of decision-making in marine shipping and the wide range of criteria we document as relevant to stakeholders is a strong argument for further engagement of decision support professionals in marine shipping.

Recommendations for Decision Support Professionals

- Marine shipping professionals are highly informed on the importance of holistic or systems thinking. There is a readiness to engage in systems methodologies that cuts across a diverse range of roles in the sector. We recommend prioritizing decision support that responds to the need for and interest in systems thinking.
- Experience is highly valued and highly important in marine shipping. Decision support professionals from outside the marine industry will only be effective if they leverage existing knowledge within the field or co-create their solutions. True collaboration is essential to both quality of the analysis and legitimacy.
- Multi-criteria approaches are required across decision domains. For example, vessel design, while seemingly an engineering challenge, poses difficult trade-offs between environmental, operational and safety performance, many aspects of which integrate quantitative and qualitative data for fulsome analyses. Providing structured, user friendly and transparent methods to integrate quantitative and qualitative data that is sufficiently user friendly for sustained use is a compelling area of future research.

4.0 CCG Case Insights: Informing decisions on near-term fuel alternatives for Program Ice Breakers

4.1 Case Study Findings: Assessing Fuel Alternatives for Program Ice Breakers

In this section of the final report, we summarize our findings related to the assessment of a specific set of fuels and their holistic environmental impacts. A comprehensive review of technologies of interest to marine shipping professionals beyond those considered in our case studies is available in the **Ship Design and Technologies to Reduce Environmental Impact** report [11].

The UBC team completed a preliminary screening evaluation of the performance of a set of near term and emerging fuel technologies (**Table 2**) using a multi-criteria structured assessment framework. Its primary purpose was as a concrete starting point for an illustrative structured decision-making exercise, so should not be read as a detailed fuels comparison. That said, by considering near term and emerging fuels side by side within a common framework, the assessment process described here may be an entry point for marine operators and policymakers in understanding both what can be adopted now and what should be planned for in the years ahead.

Table 2: Marine fuel alternatives evaluated in Workshop 2 with descriptions.
Alternatives in grey are currently widely used. Light green alternatives represent near-term (e.g., by 2030) alternatives, while dark green alternatives represent longer-term alternatives (e.g., by 2050).

Alternatives	Descriptions
[Ultra-Low Sulfur] Fossil Fuels "ULSF" (e.g., ULS Marine Gas Oil, Non-Hybrid)	A conventional fossil marine fuel with reduced sulfur content (<15 ppm), used as the baseline fuel in this assessment. MGO (Marine Gas Oil) is a refined fossil fuel used widely in marine engines that is available in ultra-low sulfur forms. While Marine Diesel Oil (MDO), which may include a blend of distillates and residuals, is not an ultra-low sulfur fuel, in some cases, due to data availability, we use MDO as the fossil fuel comparator. These fuels are compatible with existing diesel engines and bunkering infrastructure. Despite their operational reliability, they are high in greenhouse gas emissions.
[Ultra-Low Sulfur] Fossil Fuel (MGO or MDO, Battery Hybrid)	A propulsion system combining fossil fuel with battery energy storage. Batteries are typically recharged via onboard generators or shore power.
Biodiesel (e.g., Soy Oil FAME)	A bio-based fuel produced via transesterification, commonly using vegetable oils such as soy oil. It is assessed in blends such as B20 and B100, where "B20" indicates 20% biodiesel (B100) mixed with 80% petroleum diesel such as ultra-low sulfur fossil fuel. Blends below B20 can typically be used directly with existing diesel engines and infrastructure. Blends above B20 may face challenges such as reduced cold weather performance, microbial growth, and reduced storage stability. Biodiesel is considered a practical near-term alternative due to its compatibility with current systems and growing operational use.

Alternatives	Descriptions
Biodiesel + Battery (e.g., Soy Oil Biodiesel, Battery Hybrid)	Combines biodiesel with a battery electric system to optimize low-load efficiency and reduce emissions.
Renewable Diesel (e.g., hydrotreated waste cooking oil)	A drop-in hydrotreated fuel produced from waste products such as waste cooking oil, chemically similar to petroleum diesel. It offers better cold weather performance compared to biodiesel and is fully compatible with existing marine engines and infrastructure. However, domestic production in Canada is still limited, with most current supply imported from the U.S.
Renewable Diesel Hybrid	Combines renewable diesel with a battery electric system to optimize low-load efficiency and reduce emissions.
Hydrogen	Hydrogen can be produced in several ways: most commonly through natural gas reforming (grey hydrogen, which has limited CO_2 reduction potential), or through electrolysis, where water is split into hydrogen and oxygen using electricity. If the electricity is renewable, this results in green hydrogen, which is a low carbon fuel. There is also blue hydrogen, where carbon capture technology is adapted to fossil-based production. While green hydrogen offers the greatest emissions benefit, it is currently expensive and infrastructure-intensive, making it a longer-term option.
Ammonia	Ammonia is produced by combining hydrogen with nitrogen via the Haber-Bosch process. The carbon footprint depends on how the hydrogen is sourced: if it's grey or blue hydrogen, ammonia production has higher emissions; if made from green hydrogen, it becomes a low-carbon or carbon-free fuel. Ammonia production is energy-intensive, and marine use faces challenges related to toxicity and lack of infrastructure systems.
Methanol	Methanol can be produced from natural gas, biomass, or captured CO_2 with green hydrogen. It can be used in modified engines with additional cost, has low energy density, is toxic, and may increase NOx emissions. While renewable methanol offers emissions benefits, it's not widely available yet.

Researchers evaluated the performance of these alternatives against a set of criteria elicited through structured decision-making workshops with professionals from the CCG. Note that these performance evaluations are indicative and used as a starting point for this illustrative structured decision-making exercise: this comparison draws on a non-systematic review of grey and academic literature sources available during the research period, and so may not reflect recent technological developments.

We then combined those performance scores with preference modeling to rank these alternatives from most to least preferred. Emerging fuels such as hydrogen, ammonia, and methanol were excluded from the preference ranking exercises, given more limited quantitative performance data; however, they were later assessed qualitatively, based on discussions occurring during the preference modeling workshop. Criteria against which the technologies were judged are provided in (Appendix A) and a subset are summarized briefly in

Table 3, which includes preliminary performance assessments.

Preference rankings based on direct intuition and rankings based on utility scores (combining performance scores with weights reflecting the relative importance of criteria), are summarized in **Table 4**. We include rankings based on both best-case and worst-case scenarios. These distinctions refer to conditions in which there is uncertainty around lifecycle GHG emissions and other pollutants. We see a ranking change when technologies are assumed to perform to their best assumed potential in terms of low lifecycle GHG emissions as opposed to when we assume the higher GHG emissions possibilities.

Pre-workshop direct ranking (first column) occurred before participants saw the results of performance evaluations and took part in workshop deliberations and is considered a baseline ranking. Post-workshop direct ranking is the ranking of alternatives after extensive deliberation and consideration of performance evaluations. Utility-based rankings are produced indirectly by combining performance scores with weights assigned to criteria. This is a more systematic approach to ranking that avoids anchoring on favored technologies. All rankings are produced by aggregating the inputs of individuals in the workshop.

Table 3: Preliminary performance comparison of selected marine alternatives across key evaluation objectives, used as an input to preference modelling exercise.[1]

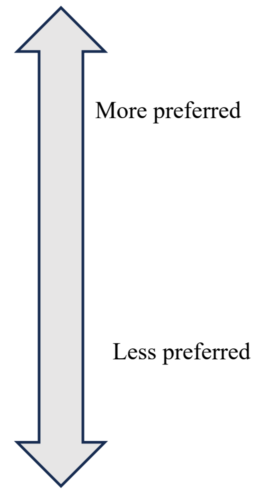
Objective	Performance Measure	Unit	Preferred Direction	Ultra Low Sulfur Fossil Fuel MGO or MDO	Ultra Low Sulfur Fossil Fuel (e.g. MGO) + Battery MGO or MDO	Biodiesel - B100 Soy Oil (transesterification)	Biodiesel Blend - B20 Soy Oil (transesterification)	Biodiesel + Battery Soy Oil (transesterification) B100	Renewable diesel Waste Cooking Oil (hydroprocessing)	Renewable diesel + Battery Waste Cooking Oil (hydroprocessing)
Cost of energy	Cost/kWh energy	$/MWh	lower	86		110			140	
Capital cost	Cost/kWh energy	$/kWh	lower							
Volumetric Energy Density	Volumetric Energy Density (higher heating value)	kWh per gallon	higher	37.66	37.66	35	35	35	36	36
Gravimetric Energy Density	Gravimetric Energy Density	kWh/kg	higher	11.88	11.88	10.81	10.81	10.81	12.29	12.29
Technology Readiness Level										
TRL - Resources	LLoyd's Register TRL Score (adapted)	Constructed Scale	higher	9	9	9	9	9	9	9
TRL - Production	LLoyd's Register TRL Score (adapted)	Constructed Scale	higher	9	8	9	9	8	9	8
TRL - Bunkering and Port Integration	LLoyd's Register TRL Score (adapted)	Constructed Scale	higher	9	9	6	8	8	9	9
TRL - Onboard Handling and Storage	LLoyd's Register TRL Score (adapted)	Constructed Scale	higher	9	7	6	9	7	9	7
TRL - Propulsion	LLoyd's Register TRL Score (adapted)	Constructed Scale	higher	9	9	6	9	9	9	9
Supply Chain Vulnerability										
SCV - Resources	SCV Level	Constructed Scale	lower	Low	Low	High	Medium	High	High	High
SCV - Production	SCV Level	Constructed Scale	lower	Low	Low	Medium	Low	Medium	High	High
SCV - Bunkering and Port Integration	SCV Level	Constructed Scale	lower	Low	Low	High	Medium	High	Low	Low
Lifecycle GHG emissions: Best Case	Lifecycle GHG emissions per unit energy	g CO2eq/MJ using 100-year GWP	lower	89	89	14.8	74.16	14.8	20	20
Lifecycle GHG emissions: Worst Case	Lifecycle GHG emissions per unit energy	g CO2eq/MJ using 100-year GWP	lower	89	89	188	109	188	250	250
Soot (Black Carbon) Emissions: High Load	BC Emission Factor (normalized)	Dimensionless	lower	1		0.4			0.85	
Soot (Black Carbon) Emissions: Low Load	BC Emission Factor (normalized)	Dimensionless	lower	1		0.32			1	
Fine Particulate Matter Emissions: High Load	PM2.5 Emission Factor (normalized)	Dimensionless	lower	1			1			
Fine Particulate Matter Emissions: Low Load	PM2.5 Emission Factor (normalized)	Dimensionless	lower	1			1			
Nitrogen Oxides Emissions: High Load	NOx Emission Factor (normalized)	Dimensionless	lower	1		1.125	1.04		0.84	
Nitrogen Oxides Emissions: Low Load	NOx Emission Factor (normalized)	Dimensionless	lower	1		1.5	1.04		0.68	
Public Acceptance										
CRL - Resources	LLoyd's Register CRL Score (adapted)	Constructed Scale	higher	4	4	6	6	6	6	6
CRL - Production	LLoyd's Register CRL Score (adapted)	Constructed Scale	higher	4	4	5	5	5	5	5
CRL - Bunkering and Port Integration	LLoyd's Register CRL Score (adapted)	Constructed Scale	higher	5	5	4	5	4	5	5
CRL - Onboard Operation	LLoyd's Register CRL Score (adapted)	Constructed Scale	higher	5	2	5	5	2	5	2

Less Preferred		More Preffered

[1] Note that these assessments are indicative and used as a starting point for this illustrative structured decision-making exercise: this comparison draws on a non-systematic review of grey and academic literature sources available during the research period, and so may not reflect recent technological developments.

Table 4: Survey ranking results. Shaded alternatives are equally preferred.

Survey 1: Pre-workshop direct ranking	Survey 2: Post-workshop direct ranking	Ranking based on Gross Utility Score –best case scenario	Ranking based on Gross Utility Score –worst case scenario
ULSF	Biodiesel blend (B20)	Renewable diesel	ULSF
Biodiesel blend (B20)	ULSF	ULSF	ULSF+battery
ULSF + battery	ULSF + battery	Renewable diesel+battery	Renewable diesel
Renewable diesel	Biodiesel + battery	ULSF+battery	Renewable diesel + battery
Renewable diesel + battery	Renewable diesel + battery	Biodiesel (B20)	Biodiesel (B20)
Biodiesel + battery	Renewable diesel	Biodiesel (B100)	Biodiesel (B100)
Biodiesel (B100)	Biodiesel (B100)	Biodiesel+battery	Biodiesel + battery



ULSF performs well under all conditions, both when participants are directly ranking alternatives before and after deliberations and when utility scores are used to rank alternatives. On the other hand, Biodiesel (B20) is evaluated as more desirable when participants directly rank alternatives, with a lower ranking when utility scores are applied.

It is important to note that in their evaluations, all assumptions of performance and preference gathering were rooted in design considerations for Program Ice Breaker vessels and may not be transferrable to other vessel classes. Moreover, since our participants were aware that this was a hypothetical exercise, they may have explored ideas and preferences that would not be considered in a high-stakes decision context. As such, we suggest caution in interpreting these technology rankings for purposes beyond this study. However, the researcher's performance evaluations and structured discussions arising during the preference elicitation workshop indicate a wide range of considerations and trade-offs that are informative beyond this context.

Observations around trade-offs across the set of alternatives, from preliminary analysis:

- Renewable diesel is the most expensive of the fuels considered, while B100 sits roughly halfway between conventional marine fuels and renewable diesel [27]. This difference reflects both feedstock prices and production constraints.
- B100 has a slightly lower volumetric energy density compared to conventional marine fuels and renewable diesel, but the gap is small and unlikely to be a major operational constraint [28].
- All three fuels are mature in core technology [29]. However, B100 scores lower for bunkering and port operations due to the need for specialized storage and handling. CCG participants

with operational experience noted reservations about technology maturity for this aspect, in a Program Ice Breaker context.

- Supply chains for conventional marine fuels are well established. In contrast, both B100 and renewable diesel face high feedstock vulnerability due to strong domestic and global competition [30]. At the B20 blend level, domestic feedstocks are sufficient to meet demand, but scaling to B100 would require much higher production. Renewable diesel faces added vulnerability at the production stage, as Canada lacks domestic facilities and depends heavily on imports (primarily from the U.S.), making supply more sensitive to international market changes [30]. At the distribution stage, bunkering and port integration are most vulnerable for B100 because of its storage requirements.
- Lifecycle GHG reductions for biodiesel and renewable diesel can reach –78% to –83% per unit of energy in best-case scenarios [31], [32]. However, indirect emissions from land-use change, feedstock substitution, and waste oil fraud can significantly reduce or negate these benefits, leading to potentially increased emissions by approximately 110% and 170% for vegetable oil biodiesel and waste cooking oil renewable diesel, respectively [32]. This highlights the importance of prioritizing upstream supply chains where emissions reductions can be verified.
- Air pollutant impacts also vary. Early pilot data suggest B100 can reduce black carbon emissions at both high and low loads, but may increase NOx emissions, with the amount depending on load [33]. Renewable diesel shows similar black carbon performance and slight NOx improvements. Battery-hybrid systems could help mitigate trade-offs, especially at low loads, by switching to battery power near ports and coastal areas. In the Arctic, black carbon reduction is particularly important due to its climate-forcing effects.
- Community readiness is assessed by Lloyd's Register to be generally lower for battery-hybrid systems as compared to their non-hybrid versions [29], as regulations for marine electrification at this scale are still evolving. B100 also scores lower due to handling and storage requirements [29].

4.2 Project Key Findings: Insights from Decision Analysis

There is no dominant technological winner, judgments are sensitive to expertise, role and uncertainty. Communication among experts across the design and decision-making chain provides opportunities for learning and alignment. Pilot projects and data sharing are critical to reducing uncertainty around future vessel technologies.

Preference modeling with workshop participants indicated a wide range of opinions over alternative fuels for the Program Ice Breaker, with lack of consensus on most and least preferred options. For example, Renewable Diesel + Batteries is evaluated by three participants as their top choice, and by another three participants as their least preferred alternative. This pattern may reflect the many different professional roles involved in vessel design and procurement (and present in our workshop) and uncertainty around the performance of some alternatives.

We noted a higher consensus on the second direct ranking survey than the first in the CCG workshop. This could be a product of the discussion and criteria weighting exercises leading to genuine consensus building or because the discussion created a more shared understanding of definitions around the alternatives- essentially revealing a pre-existing consensus that was obscured by definitional misunderstandings. However, two participants did not complete both direct ranking exercises, so it could also be a result of the change in participant numbers. If the first interpretation is supported in future studies, it would send a strong signal for increased shared engagement among professionals at different stages in the vessel design and procurement process. The common approach to vessel design integrates many expert roles in a traditional design spiral (**Figure 3)** providing an iterative structure affording each role opportunities to ensure compliance to its own constraints. Using our SDM approach, however, professionals work together to develop shared understandings of goals and performance. We suggest that integrating SDM throughout more traditional decision processes may enhance institutional expertise and decision outcomes.

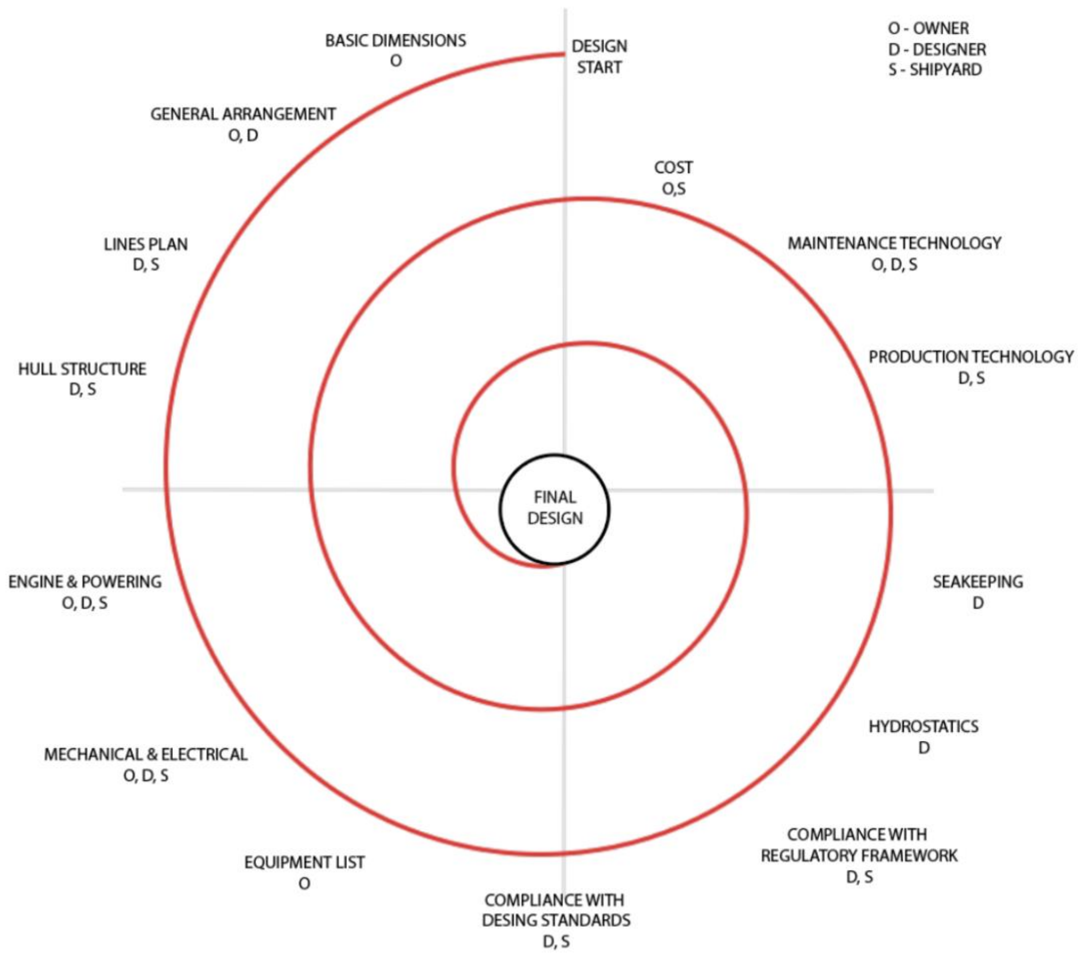


Figure 3: Naval architecture design spiral, reproduced from [11].

Decision support will look different throughout the sector and at different stages in decision-making and design. The cost and effort for advanced multi-criteria decision analysis is not always justified depending on the specifics of the decision at hand including the informational landscape and presence of dominating criteria.

In the CCG case study, direct rating and utility score rankings are not aligned. For example, direct ranking discounts renewable diesel options and overstates the performance of biodiesel (B20) as compared to utility scores. While difference in alignment could be attributed to several factors (preferences are based on objectives neglected in the criteria set, direct rankings are overlooking considerations, number of participants) it is likely important that UBC researchers provided performance metrics derived from external sources. As such, the performance scores used in calculating utility scores may have included new information that was not available to participants when making intuitive judgments in the first direct ranking exercise. If this interpretation is validated elsewhere, it indicates that the added costs and effort in developing utility scores are not always warranted given the informational landscape and should be targeted to decisions with high informational demands that challenge expert intuitions.

Informational demands are not the only consideration in targeting decision support.

Dominating constraints can reduce the impact of multi-criteria decision analysis. For example, one CCG participant explained that uncertainty around what the future will look like even 10-15 years down the road means that flexibility is a dominating design heuristic. This dominance of flexibility was echoed by both technical participants and those in strategic/policy domains, but another participant countered that risk considerations dominated their decisions. Preferences, at the level of detail explored in MCDA, are further discounted because of factors beyond the participant's control, such as international regulations and port compatibility. We recommend engaging in problem structuring activities even when there is an assumption of dominating constraints, as the early stages of structured decision-making can expand the set of alternatives recognized by decision-makers. Finally, scale of decision-making matters, with one participant suggesting that decision support would have more of an impact at the strategic level of decision-making rather than design, as designed is a more constrained decision space.

5.0 NRC Case Insights: Supporting evaluation of research and development opportunities

5.1 Case Study Findings: Key Performance Indicators for R&D Evaluations

In this section of the final report, we summarize our findings related to identifying key performance criteria for evaluating R&D proposals in the NRC's Ocean Program. We summarize the illustrative set objectives generated and how they were integrated into a multi-criteria evaluation framework to evaluate a hypothetical set of proposals.

From expertise elicited during case study interviews, we generated an illustrative list of objectives that can serve as candidate criteria in evaluating R&D projects for the NRC Oceans Program (**Table 5**). These were then refined during our second NRC Workshop. Additional guidance on potential impact mechanisms and indicators is provided in Appendix B.

Table 5: List of illustrative objectives and sub-objectives.

*Objectives marked with * were revised or expanded based on feedback at the second workshop. As a result, some objectives or sub-objectives may not be included or have different phrasing (e.g., organizational continuity instead of alignment) in the results from the evaluation exercises presented below.*

Objectives	Definitions
Protect the physical environment	
Mitigate climate change	To align with or contribute to Canada's latest nationally determined contributions i.e., a GHG emissions reduction target of 45-50% below 2005 levels, and its commitment to net-zero by 2050
Improve air quality	To minimize the emissions of other air pollutants generated by the marine sector e.g., SOx, NOx, volatile organic compounds
Improve water quality	To minimize the releases of chemical/pathogenic/biological contamination of concern
Maintain shoreline/sediment integrity	To maintain shoreline/sediment integrity
Mitigate underwater ocean noise	To reduce underwater ocean noise, defined as human-generated sounds that are transmitted beneath the surface of the water and have a wide range of impacts on marine animals
Other	Other aspects of the Physical Environment not covered above.
Protect the biological environment	
Promote conservation and biodiversity	To reduce the negative impacts of vessel activities on species conservation and biodiversity
	To mitigate occurrence and the impacts of invasive species carried by vessel activities
	To reduce the negative impacts of vessel activities on fish and fish habitat
	To reduce the negative impacts of vessel activities on marine mammals
Other	Other aspects of the Biological Environment not covered above.

Protect the socio-environment	
Respect Indigenous knowledge	To identify and understand the potential impacts of the research project on Indigenous peoples and their rights, including their lands, territories and resources, and to incorporate Indigenous knowledge with consent into the project
Respect Indigenous marine uses (IMUs)	To understand the current and future pressures of vessel traffic on IMUs in each First Nations' territory, and to co-develop potential management recommendations that can be implemented to address adverse effects on IMUs, when and where necessary
Facilitate equitable fisheries access and prosperity	To ensure the combination of fish harvesters' rights and capacities, that confer their ability to harvest and benefit from fisheries
Facilitate sustainable marine recreational activities	To allow marine recreation (i.e., activities, sports or games engaged in for leisure and enjoyment taking place in the marine environment) without harming the future use by others. Examples of marine recreation include recreational fishing, cruise ship travel, whale watching, diving, kayaking, sailing, and visiting beaches and other marine locations
Enhance climate adaptation and climate resilience	Adaptation refers to adjustments in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects. It refers to changes in processes, practices and structures to moderate potential damages or to benefit from opportunities associated with climate change
Other	Other aspects of the socio-environment not covered above.
Organizational alignment*	
Align with the broader Government of Canada's strategies and values	To timely align with the priorities of the Government of Canada
Align with the NRC's strategies and values	To timely align with the priorities of the National Research Council
Enhance organizational efficiency	To improve the operational efficiency of the NRC and its ability to deliver impacts within certain time and capacity
Ensure organizational continuity	To ensure the program generate revenue for sustainable and growing operations
Other	Other aspects of Organizational Continuity not covered above.
National security	
National security	To protect the safety and security of Canadians both at home and abroad, as well as Canadians' businesses and interests
Other	Other aspects of National Security not covered above.
Well-being of mariners and maritime professionals	
Mariner safety	To ensure the well-being and security of those working on a vessel
Mariner habitability	To ensure acceptability of the conditions of a vessel in terms of whole-body vibration, noise, indoor climate, and lighting, as well as physical and spatial characteristics, according to prevailing research and standards for human efficiency and comfort
Other	Other aspects of Well-being of Mariners and Maritime Professionals not covered above.

Social equity and inclusiveness	
Stakeholder engagement and inclusiveness	To engage a wide range of stakeholders and ensure that the concerns and values of various stakeholder groups are taken into account when identifying research areas or projects to support
Knowledge generation and mobilization	To enhance the sharing and uptake of information across governmental agencies, businesses, and/or with broader society
Other	Other aspects of Social Equity and Inclusiveness not covered above.
Canadian workforce and capabilities*	
Build resilient Canadian workforce and capabilities	To build Canadian workforce and capabilities that could bring economic prosperity in the present and future

These objectives served as the evaluative criteria against which a set of hypothetical projects were evaluated using a structured decision-making approach, which is summarized in **Table 6.**

Table 6: Summary of four hypothetical proposals

Objectives	Approach	Innovation
Proposal A: Autonomous Deep-Sea Carbon Sequestration Platforms		
Deploy autonomous underwater platforms for deep-sea carbon sequestration	• Extract dissolved CO_2 from seawater, form carbonate minerals, deposit onto the ocean floor • Prototype validation, mineralization optimization, ecological safety assessment	Combines subsea robotics, marine geochemistry, and environmental monitoring
Proposal B: Enhanced Monitoring Network for Marine Protected Areas		
Strengthen management of MPAs through expanded sensor monitoring networks	• Deploy satellite, aerial, underwater, and surface-based sensors • Real-time data integration into accessible management platforms	Comprehensive, continuous environmental and activity monitoring system
Proposal C: Bio-inspired Hull Coatings to Eliminate Marine Fouling		
Develop environmentally friendly marine coatings inspired by biological surfaces	• Investigate natural anti-fouling surfaces (e.g., shark skin), synthesize bio-inspired coatings • Conduct computational modeling and real-world vessel testing	Non-toxic, durable, biomimicry-based hull coatings
Proposal D: Retrofitting Cargo Ships with Wind-Assisted Propulsion Systems		
Facilitate adoption of wind-assisted propulsion to cut maritime emissions	• Evaluate optimal wind-assist retrofit designs (rotor sails, kite sails, rigid wings) • Demonstrate feasibility through vessel retrofits and operational trials	Practical application of established wind-assist technologies for existing ships

Two qualitative scales were developed to evaluate the proposals, considering both scale and likelihood of impacts for each of the objective categories (**Table 7** and **Table 8**). The projected scale and likelihood of impacts are adapted from Canada's New Frontiers in Research Fund Research Fund merit indicators [34]. 'Scale of Potential Impact' evaluates the breadth and magnitude of the expected impact if the proposal is successfully implemented. 'Likelihood of Potential Impact' assesses the probability that the proposal will effectively contribute to achieving its intended goal(s). The two dimensions are converted into numerical values as for calculating the weighted scores of sub-objectives.

Table 7: Description of scale of potential impact

Level	Score	Description
N/A	0	No potential impact on this objective described.
Limited	1	Impact is identified but small in magnitude, or restricted to a narrow application context (e.g., communities, region, timeframe, sector), with limited ability to scale beyond.
Moderate	2	Impact is meaningful in magnitude, for given application context, with potential to scale beyond.
Substantial	3	Major magnitude of impact; targets a substantial fraction, with multiple application contexts (e.g., communities, region, timeframe, sectors).
Transformational	4	Magnitude of impact is systemic; shifts understanding in paradigmatic way, or technology, policies, practice, and behaviors at scale.

Table 8: Description of likelihood of potential impact

Level	Score	Description
N/A	0	No potential impact on this objective described.
Very Unlikely	0	No clear mechanism for achieving the objective; significant barriers with no feasible mitigation.
Unlikely	1	Weak causal link to the objective; major obstacles exist with limited plans to address them.
Moderate	2	Some evidence supporting effectiveness; challenges exist, but partial strategies for overcoming them are provided.
Likely	3	Clear mechanism for impact with supporting evidence and rationale; most obstacles have feasible solutions.
Very Likely	4	Mechanisms for impact well-supported by robust evidence, theory, or precedent; few barriers, with clear and effective mitigation strategies.

Several key findings were elicited from the proposal evaluation exercise in Workshop 2. First, the gut judgment of most workshop participants aligned with their own multi-criteria evaluation results, as evidenced by the individual comparison between direct and utility-based weighted ranking scores in **Table 99**. Second, although the numerical rankings of the four proposals were mostly consistent across participants, the weighted scores derived from the multi-criteria evaluation process varied greatly for the same proposals (**Table 1010**). This substantial difference stemmed from the wide variation in participants' interpretation and perceptions of the scale and likelihood of impacts associated with the proposals (see **Figure 4** for an illustrative example, for variation in assessments of scale of impact for sub-objectives across participants). Participants were generally consistent in their weightings of the relative importance of the eight major objectives overall, and our counterfactual scenario analysis showed that participants' baseline weightings led to minor shifts in proposal rankings but notable changes in the actual scores.

Table 99: Individual comparison between direct and weighted ranking results of the four proposals

	Ranking of proposals			
	1st (Highest)	2nd	3rd	4th (Lowest)
$P1_{direct}$	C	A	D	B
$P1_{weighted}$	A	C	B	D
$P2_{direct}$	B	C	D	A
$P2_{weighted}$	B	C	D	A
$P3_{direct}$	Not provided			
$P3_{weighted}$	D	C	B	A
$P4_{direct}$	B	C	A	D
$P4_{weighted}$	B	C	A	D
$P5_{direct}$	B	C	D	A
$P5_{weighted}$	B	C	D	A

Table 1010: Statistics of the proposals' final weighted scores

Proposal	Mean	Standard deviation	Maximum	Minimum	Range
A: Autonomous Deep-Sea Carbon Sequestration Platforms	25.8	14.6	43.0 (P1)	11.5 (P2)	31.5
B: Enhanced Monitoring Network for Marine Protected Areas	46.5	9.6	60.5 (P2)	38.4 (P1)	22.2
C: Bio-inspired Hull Coatings to Eliminate Marine Fouling	36.9	8.5	46.8 (P3)	26.7 (P2)	20.1
D: Retrofitting Existing Cargo Ships with Wind-Assisted Propulsion Systems	29.5	14.1	51.7 (P3)	18.3 (P4)	33.4

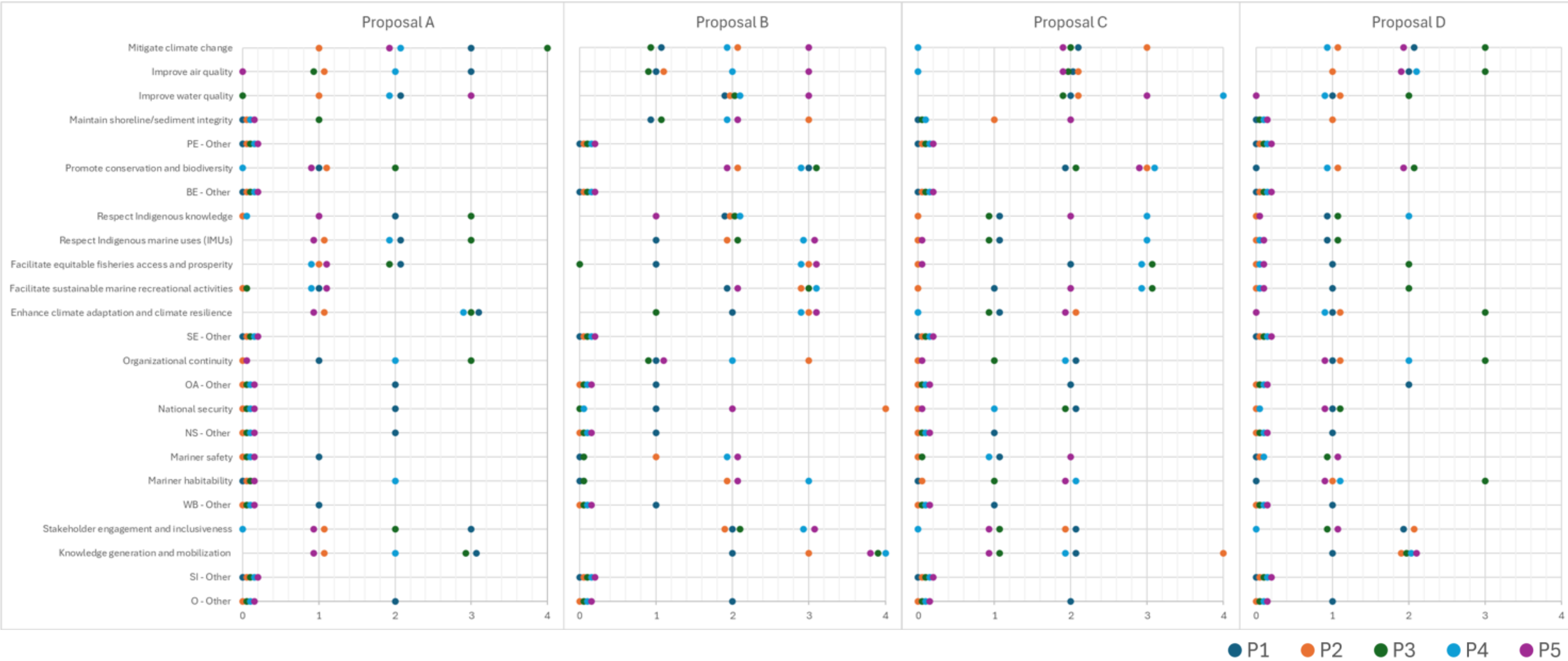


Figure 4: Distribution of the perceived scale of impacts across sub-objectives by participants.

Remarks: (1) The "other" sub-objectives under the objectives are indicated in short form as: Protect the physical environment (PE), Protect the biological environment (BE), Protect the socio-environment (SE), Organizational alignment (OA), National security (NS), Well-being of mariners and maritime professionals (WB), Social equity and inclusiveness (SI), Other (O).
(2) In the horizontal axis, 0 refers to N/A; 1 refers to limited impact; 2 refers to moderate impact; 3 refers to substantial impact; 4 refers to transformational impact.

These findings suggest that while participants share similar preferences for the proposals, their choices could be grounded in different reasonings and justifications. Although a direct ranking approach is less resource-intensive, it does not reveal a proposal's positive and/or negative implications for the values and interests of participants. The structured process of designing objectives and sub-objectives, allocating baseline weightings, and determining the scale and likelihood of impact encouraged in-depth discussions among participants to define their valued components, assess whether a proposal could address them, and explore any trade-offs between those components. Such iterative and collaborative process is considered by participants to be useful for reaching a justified conclusion, especially for competitions that involve substantial funding or projects that could span over decades with far-reaching impacts.

5.2 Project Key Findings: Insights for Decision Analysis

During the problem structuring phase, organizations can strategically assess level and need for consensus—both for the meaning of objectives, and their relative importance. As participants shared their perspectives on how the initial evaluation framework could be revised to better reflect their topics of concern or valued components, there were differing opinions on how to decide whether a valued component is an objective or a sub-objective. For instance, some of the valued components proposed by participants, such as advancing research and innovation, could be cross-cutting and applicable to multiple objectives. These discussions highlighted the importance of the problem structuring phase, as agreed-upon large-scale goals, such as "organizational alignment," may be operationalized differently across actors. In this sense, there is value in investing time to explicitly define objectives, even when they are widely agreed upon as important.

Likewise, while the workshop calculated weighted scores with different individuals' baseline weightings, in practice, the baseline should be discussed and agreed upon by the participants prior to any project evaluation. The ratio between scale and likelihood of impact would depend on factors such as the purpose of a given competition and the expected time to market. For example, if the funding prioritizes a higher return on investment or aims at addressing an urgent issue, the evaluation should place greater emphasis on likelihood of impact rather than the scale. Similarly for weightings of objectives and sub-objectives, if the purpose of a competition is climate change mitigation, then this sub-objective should by default be allocated higher weighting than others. There are a range of tools and techniques to support problem structuring of varying levels of complexity, ranging from the facilitated interactive workshops we conducted, to more simple surveys and polls. Factors such as the potential impact of decision-making (e.g., size of a funding program), urgency, and degree of existing consensus can be used to select decision-support techniques. Whether these decisions are made collaboratively or decided through a top-down approach, transparency is critical.

Attitudes towards uncertainty may differ between investment in R&D and investment in technology deployment; in R&D there is a role for both high risk-high reward projects, and sure bets. Participants suggested that different ratios should be used for projects with varying levels of technology readiness. In practice, projects with similar Technology Readiness Levels (TRLs) are evaluated within the same group. For higher-TRL projects, likelihood of impact would be of greater interest, whereas more transformative, lower-TRL proposals, evaluation should place more emphasis on the scale of impact. Compared to organizations that are focused on tactical deployment of technologies, R&D organizations may have a mandate to support high risk, but potentially transformative proposals. In these contexts, high uncertainty is not necessarily an attribute to be avoided.

6.0 Concluding Thoughts

The United Nations General Assembly designated 2021-2030 to be the 'Ocean Decade.' Some in the maritime shipping industry have called this a 'decade of decisions.' With regulatory regimes demanding a sustainable industry along the full supply chain of the shipping sector and a wide range of technologies available to meet those goals, the high volume of decisions is apparent. But the challenges do not end with the need to manage a crowded decision space. Uncertainty around how alternative technologies perform is high especially when the scope of analysis is expanded beyond limited considerations to a more systemic approach. Evolving concerns around methane emissions from LNG production, and concern around the water quality impacts of scrubbers illustrate the impact of analytic scope on decision making and the risks that siloed decision making pose to identifying trade-offs.

What is possibly even more daunting is the changing nature of the decisions the industry faces – questions of competing values, not ratios of cost and benefits for which industry is well equipped and experienced in facing: Do we reduce sulfur emissions with scrubbers, protecting the air at a cost to oceans? How do we manage the transition to low carbon fuels without imposing new risks to mariners? Where should we spend our efforts – reducing underwater noise that threatens marine mammals or reducing climate forcing emissions?

While industry is experienced and effective at cost-benefit analysis and optimization, these approaches do not meet the moment, distinguished as it is by a high volume of interdependent decisions, from cost and operational logistics to irreconcilable values. This decade of decisions is best addressed by coupling systems design and decision analysis. Systems methods help us to make sense of the complex maritime environment, while decision analysis guides our choices within it. Guided by this perspective, we examined two different decision arenas in maritime shipping to develop a decision support framework informed by best practices in decision analysis and supported by systems techniques.

Through engagement with three arenas of decision-making (industry, Canadian Coast Guard, National Research Council, Canada), we conducted two distinct case studies spanning tactical and strategic decisions around vessel design and research and development, respectively. We observed an openness to systems thinking based on, at times, professional knowledge and at other times an intuitive and experience-based awareness. While some professionals we spoke with were experienced with decision analytic techniques, we found that their adoption in the maritime shipping industry is limited.

In our Canadian Coast Guard case study, we combined systems and decision analytic methods to generate a comprehensive list of objectives for vessel design and then evaluated a set of energy alternatives against those objectives. The structured decision-making methods we employed are distinct from a sequentially organized design spiral because they bring decision-makers with different goals and jurisdictions together at the same time to co-develop a shared understanding of priorities and alternatives, rather than ensuring compliance independently and iteratively throughout the process. In our National Research Council, Canada case study our systems and decision analytic approaches helped us to generate a set of coherent objectives and indicators with an interdisciplinary team of researchers. We then operationalized a set of key performance indicators for evaluating research proposals.

Despite the differences in our case study arenas – one focusing on short-medium term design decisions and the other in long-term research and development evaluation, we observed striking similarities across concerns and objectives, a shared sensitivity to the importance of systems thinking, and acknowledged tension between urgency around reducing environmental impacts and insulating safety and operational requirements from risk.

Both case study groups engage in decision-making that is sufficiently complex and high stakes to justify investment in decision support, but there are significant barriers to their adoption. For example, high uncertainty around the costs and availability of future fuels means that designing for flexibility dominates other considerations, seemingly reducing the impact of multi-criteria decision-making. However, documenting and evaluating multi-criteria creates opportunities to find co-benefits among alternatives. Moreover, sequential or siloed decision-making can create misalignments – what reduces capital costs from one perspective may raise costs for operators in the long run. When strategically timed, cross-professional dialogues supported by SDM, can surface these trade-offs.

Decision analysis developed to respond to the challenges of complex, high stakes and multi-faceted decision-making; all of which are key characteristics of maritime shipping decision-making. The use of decision analysis in that sector, however, has not met its potential. In developing this framework and demonstrating a range of techniques to integrate systems thinking and decisions analysis into maritime shipping, we hope to further the development and adoption of targeted decision support to support the maritime shipping sector through its decade of decisions.

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8.0 Appendices List

Appendix A – Illustrative objectives developed through Canadian Coast Guard Workshop 1

This table provides illustrative and selective examples of potential indicators for different high-level objectives.

Criteria	Potential Indicators	Sub-indicators (if any)	(Sub-)Indicator description
Operations	Cost of Energy		The cost to produce one kilowatt-hour electricity
	Operating Cost	Fuel cost	The total fuel cost based on one year of operation
	Energy efficiency		as the ratio of useful power output delivered for propulsion to the total energy input, typically measured in terms of fuel consumed, aimed at achieving minimal energy loss while maintaining optimal vessel performance
	Gravimetric Energy Density		The amount of energy that the fuel can produce per unit of mass
	Energy intensity		The amount of energy that the fuel can produce per unit of volume
	Autonomous continuous operation	*Reliability*	The degree of reliability of a system operating in a series configuration, where failure of one component may affect the whole
	Technology Readiness Levels (TRL) with respect to various supply chain stages	TRL of the resources stage	This stage refers to basic natural resources and feedstocks from which fuels are produced. For example, biomass feedstocks and transportation from field to bio-refinery.
		TRL of the production stage	This stage includes all processing of resources and intermediate products used to create fuels. This includes: From resource to transportation at bunkering ports; Fuel storage for buffering; Transportation and distribution of intermediate and end products; Chemical processes to produce molecules (e.g. electrolysis, Haber Bosch); Integration of production systems with wider energy system
		TRL of the bunkering and port integration stage	This stage reflects the readiness of bunkering infrastructure and port systems such as refueling stations, safety zones, barge handling, and storage compatibility
		TRL of the onboard handling and storage	This stage includes the maturity of onboard fuel systems, such as tanks, piping, venting systems, and the preparedness of crew to manage them.
		TRL of the propulsion stage	This stage refers to the readiness of the propulsion system including fuel cells, internal combustion engines, hybrid technologies, and electric motors to operate with the proposed fuel.
	Work area required	Footprint	Footprint refers to the physical space occupied by the propulsion system within the vessel
	Storage and handling requirements		The specific onboard infrastructure and operational protocols needed to store, handle, and manage the fuel safely and effectively

Criteria	Potential Indicators	Sub-indicators (if any)	(Sub-)Indicator description
FRRIR (flexibility, readiness, resilience, integration, robustness)	Ease of maintenance	Availability of Spare Parts and Components	The extent to which spare parts and system components are readily available for maintenance or repair
		Frequency of Scheduled Maintenance	The recommended intervals at which preventive maintenance tasks must be carried out to ensure safe and efficient operation
		Corrosion and Material Degradation Risks	The degree to which system materials are compatible with the fuel type, including potential risks of corrosion, erosion, or premature degradation
	Flexibility: Modular friendliness / retrofittability		The ability of the fuel or propulsion system to be integrated into existing vessels or upgraded modularly without requiring full redesign.
	Maneuverability		The effect of the propulsion system on vessel handling characteristic
	Supply chain vulnerability	TRL of the resources stage	Resources refer to basic natural resources and feedstocks from which fuels are produced
		TRL of the production stage	The production stage includes all processing of resources and intermediate products used to create fuels
		TRL of the bunkering and port integration stage	This stage covers bunkering and ports integration
Crew requirements	Number of certifications required		The number and type of certifications or training modules that crew members must complete to safely operate vessels using the fuels
Crew wellbeing	Measure of produced IRN		A measure of indoor risk nuisances (IRN) such as unpleasant odors, poor air quality, or elevated humidity that may impact crew health and comfort
	Risk factor: low flash point		Low flashpoint refers to the minimum temperature at which a liquid gives off enough vapor to ignite in the presence of an ignition source
	Risk factor: new impacts to vessel in event of failure		The degree of risk associated with a fuel's low flashpoint, meaning it can ignite at lower temperatures and may require enhanced safety measures
	Crew safety	Crew safety at various nodes of the hazard identification (HAZID) process	Hazard identification (HAZID) is one of the common approaches to assess potential impacts of technology adoption on crew safety. Hazards in various "nodes" are identified, and their risk rankings are assessed "Nodes" refers to the various operational aspects of a vessel, such as navigation, external events, bunkering, ship operations other than bunkering etc.
	Crew comfort	Accommodation area	Living quarters onboard a vessel, designed to provide comfort, functionality, and safety for the crew during operations
		Whole-body vibration	Mechanical oscillations transmitted through the vessel's structure to the crew, potentially affecting comfort, health, and operational performance
		Noise	Intensity of sound produced by propulsion systems and onboard equipment, which impacts marine life, crew comfort, and regulatory compliance

Criteria	Potential Indicators	Sub-indicators (if any)	(Sub-)Indicator description
Project Management	Capital costs		One-time expense of acquiring, installing, and commissioning the equipment and infrastructure necessary for the vessel's propulsion, including engines, power systems, and auxiliary components
	Technology Readiness		The overall maturity and market readiness of the technology
	Design complexity		The level of engineering and integration difficulty involved in incorporating the propulsion system
Air impacts	CH4		Methane emissions generated across the full lifecycle of the fuel
	CO2		Carbon dioxide emissions generated across the full lifecycle of the fuel
	N2O		Nitrous oxide emissions generated across the full lifecycle of the fuel
	NH3		Ammonia emissions generated across the full lifecycle of the fuel
	NOx		
	PM 2.5		Fine particulate matter emissions (less than 2.5 microns) generated across the full lifecycle
	PM 10		Coarse particulate matter emissions (less than 10 microns) released during the lifecycle of the fuel
	Black Carbon		Black carbon (soot) emissions generated across the full lifecycle of the fuel
	SOx		Sulfur oxide emissions produced across the full lifecycle
	Refrigerants		Emissions of High-GWP refrigerants released during the lifecycle of the fuel
Land impacts	Land competition		
	Production of harmful discharges		The release of harmful by-products or pollutants to land environments at any stage of the fuel lifecycle
	Solid waste management consequences		Challenges in managing solid waste produced during the full lifecycle of the fuel
	Hazardous materials at end of life		The presence and handling of hazardous substances that arise at the end of the system's lifecycle
Water impacts	Discharges of oily water		The risk of oily water discharge to marine environments throughout the full lifecycle
	Discharges of chlorine		Chlorine discharges that may occur during any phase of the fuel lifecycle
	Discharges of phosphates		Phosphate emissions introduced to water systems throughout the lifecycle of the fuel
	Discharges of graywater		Graywater emissions generated throughout the lifecycle of the fuel
	Discharges of solid wastes		Solid waste discharges to marine environments throughout the fuel lifecycle
	Persistence of discharges		The degree to which waterborne discharges persist in the environment throughout the fuel lifecycle
Public and wellbeing	Production of URN		The extent to which the full lifecycle of the fuel or propulsion system generates undesired risk nuisances (URN)
	Provides added services		Whether the fuel or propulsion solution delivers additional social or community benefits beyond core functionality
	Levels of public acceptance with respect to various supply chain stages	Community readiness level (CRL) of the resources stage	This stage refers to basic natural resources and feedstocks from which fuels are produced. For example, Biomass feedstocks and transportation from field to bio-refinery

Criteria	Potential Indicators	Sub-indicators (if any)	(Sub-)Indicator description
		CRL of the production stage	This stage includes all processing of resources and intermediate products used to create fuels. This includes: From resource to transportation at bunkering ports; Fuel storage for buffering; Transportation and distribution of intermediate and end products; Chemical processes to produce molecules (e.g. electrolysis, Haber Bosch); Integration of production systems with wider energy system
		CRL of the bunkering and port integration stage	This stage addresses the following: Refuelling stations; Barges; Berth; Shore side storage; Venting and detection; Safety zone (including proximity to populated areas); Distribution of end product
		CRL of the onboard operation stage	This stage covers all operations onboard
Leadership	Supports Canadian businesses		Whether the implementation of the fuel or propulsion system supports domestic industry throughout the fuel lifecycle
	Indigenous content (minimum 5% for yes)		Whether the project includes at least 5% Indigenous participation through ownership, employment, procurement, or partnership across the design, construction, or operation stages
	Measure of innovation or novelty		The extent to which the fuel or propulsion system introduces new technologies, concepts, or approaches

List of selected objectives with detailed constructed Scales

Objective		Unit	Definition of Constructed Scales
Technology Readiness Levels (TRL) Adapted from Lloyd's Register	TRL - Resource TRL - Production TRL – Bunkering and Port Integration TRL – Onboard Handing and Storage TRL - Propulsion	Constructed scale	The technology readiness level indicates the maturity of a solution within the research spectrum from the conceptual stage to being marine application-ready 1 - Basic principles of concept are observed and reported. Scientific research begins to be translated into applied research and development. Activities might include paper studies of a technology's basic properties 2 - Technology concept and/or application formulated 3 - Analytical and experimental critical function and/or proof of concept. Active research and development are initiated. This includes analytical studies, laboratory studies and/or feasibility assessments 4 - Validation of integrated prototype in test environment. Basic technological components are integrated to establish that they will work together 5 - Component and/or validation in a simulated environment. The basic technological components are integrated for testing in a simulated environment 6 - System/subsystem model or prototype demonstration in a simulated environment. A model or prototype that represents a near desired configuration 7 - Prototype or pilot ready for demonstration in an appropriate operational environment 8 - Actual technology completed and qualified through tests and demonstrations. Technology has been proven to work in its final form and under expected conditions 9 - Actual technology proven through successful deployment in an operational setting. Actual application of the technology in its final form and under real-life conditions

Objective		Unit	Definition of Constructed Scales
Supply Chain Vulnerability (SCV)	SCV - Resources	Constructed scale	Low - Local feedstocks are abundantly and reliably available locally, supported by favorable environmental conditions, stable policies, and sufficient infrastructure for collection and transport. International imports are stable and supported by favorable trade agreements and consistent international demand. Policies facilitate efficient cross-border trade, ensuring access to supplementary feedstocks when needed. Transportation systems are efficient, ensuring smooth movement of feedstocks to production facilities at low cost and with negligible delays Medium - Local feedstock availability is moderately reliable, with some constraints due to environmental issues, policy changes, or competition from other sectors. Local infrastructure supports feedstock collection but occasionally faces bottlenecks. International imports are moderately accessible, with risks from fluctuating global demand, restrictive trade agreements, or policy changes in supplier countries. Market competition occasionally increases costs or delays shipments. Transportation systems are functional but subject to delays or higher costs during disruptions High - Feedstock availability is highly constrained locally and internationally, with significant risks from environmental conditions, restrictive policies, and intense market competition. Local infrastructure for feedstock collection is underdeveloped. International imports are unreliable due to unfavorable trade agreements, restrictive export policies from supplier countries, or high global demand driving up costs. Supply chains are frequently disrupted by geopolitical tensions or inconsistent international regulations. Transportation systems are inefficient or inadequate, leading to frequent delays, high costs, and risks of supply chain disruption
	SCV - Production		Low - Local production facilities are well-established locally, with consistent access to required inputs. Infrastructure is modern and supports efficient operations. Environmental factors have minimal impact on production processes, and policies encourage stable operations. International fuel imports are stable and supported by trade agreements. Transportation systems enable seamless movement of finished products to storage or bunkering sites at low cost and with high reliability Medium - Low production facilities are present locally but face occasional constraints from input shortages, infrastructure limitations, or fluctuating costs. Environmental conditions and policy changes periodically disrupt production processes. International production options exist but are limited by trade or cost considerations. Transportation systems function but may experience delays or increased costs during peak demand or adverse conditions High - Local production is minimal or highly constrained by insufficient infrastructure, high input costs, or limited access to necessary inputs. Production depends heavily on international imports of intermediate products, which are unreliable due to restrictive trade agreements, high global demand, or adverse policy environments in supplier countries. Transportation systems are inadequate, leading to frequent delays and high costs for moving products to storage or bunkering sites

Objective		Unit	Definition of Constructed Scales
	SCV – Bunkering and Port Integration		Low - Ports and bunkering infrastructure are well-equipped to handle biofuels, with efficient storage, delivery, and distribution systems. Local ports provide stable fuel supplies supported by favorable policies, low costs, and minimal environmental risks. International fuel supplies are readily available, with robust trade networks ensuring timely imports. Transportation systems within ports are efficient, enabling seamless bunkering operations Medium - Ports and bunkering infrastructure are functional but face occasional challenges in adapting to biofuels, such as limited storage capacity or compatibility issues. Environmental conditions and policy requirements sometimes disrupt operations. International fuel supplies are accessible but may experience cost fluctuations or delays due to trade barriers. Transportation systems are moderately efficient, with occasional inefficiencies in moving fuel to vessels High - Ports and bunkering infrastructure are inadequate, with significant challenges in handling biofuels, such as outdated systems, insufficient storage, or high costs. Environmental factors frequently disrupt operations, and policies may further complicate compliance. International fuel supplies are unreliable due to trade restrictions, geopolitical risks, or high costs. Transportation systems within ports are inefficient, leading to delays and risks of supply chain disruptions
Public Acceptance	CRL - Resources CRL - Production CRL – Bunkering and Port Integration CRL – Onboard Handing and Storage	Constructed scale	Adapted from the Lloyd's Register Zero Carbon Fuel Monitor, the community readiness level indicates the societal maturity of a marine solution in terms of acceptability and adoption by both people and organizations 1 - Public support or opposition is hypothetical or unclear, possibly because the technology is not introduced to the market via trials and pilot projects, or the adoption of that technology is more prominent in other regions 2 - Public support or opposition is becoming understood as a result of pilots. 3 - Early-stage solutions (e.g., draft regulatory frameworks, technical studies, risk assessments) are being formed and communicated to the public to tackle their concerns 4 - Evidence that supports the adoption of the technology becomes widespread, resulting in initial public acceptance. Public opinions on the technology are divisive 5 - There are increased transparency and formalized processes to resolve stakeholder issues, yet public opposition can still be observed 6 - Well-defined processes are available to resolve stakeholder issues, the technology has obtained widespread public acceptance
Soot (Black Carbon) Emissions: High & Low Load		Dimensionless	Emission factor values (g/kWh) normalized to 1, based on diesel in given engine test
Fine Particulate Matter Emissions: High & Low Load		Dimensionless	Emission factor values (g/kWh) normalized to 1, based on diesel in given engine test
Nitrogen Oxides Emissions: High & Low Load		Dimensionless	Emission factor values (g/kWh) normalized to 1, based on diesel in given engine test

Appendix B – Illustrative key performance indicators developed through National Research Council workshops 1 and 2

This table provides illustrative and selective examples of mechanisms and indicators for different high-level objectives.

Objective	Definition	Potential mechanisms	Potential Indicators	Additional context notes
Physical environment				
Mitigate climate change	To align with or contribute to Canada's latest nationally determined contributions i.e., a GHG emissions reduction target of 45-50% below 2005 levels, and its commitment to net-zero by 2050	Increase the portion of low-emissions fuel adoption rates compared to that of petroleum-based fuels	- Increase in the annual production volume of certain fuel or the material(s) required to produce the fuel - Change in the technology readiness level of a technology	- More about the biodiesel production in Canada from 2010 to 2023 is available at https://www.statista.com/statistics/485400/total-biodiesel-canadian-production/ - More about the hydrogen production potential in Canada is available at https://natural-resources.canada.ca/energy-sources/clean-fuels/producing-hydrogen-canada - The adoption of alternative marine fuels should consider the overall impacts under different circumstances. For example, incomplete combustion of ammonia could produce N2O, which has even higher GWP than CO2. Relevant study: www.sciencedirect.com/science/article/pii/S1540748918306345
		Reduce the GHG emissions intensity of activities within the supply chain of marine fuels	- % of reduction in tank-to-wake / well-to-wake GHG emissions	- The International Council on Clean Transportation gives an overview of the well-to-wake emission factors of conventional marine fuels. Details are available at https://theicct.org/wp-content/uploads/2021/06/Well-to-wake-co2-mar2021-2.pdf
		Develop lower-emissions and/or energy-efficient technologies	- % of reduction in tank-to-wake / well-to-wake GHG emissions	- Same as above
		Increase the sequestration of GHG emissions via natural or technological means e.g., forests or Carbon Capture, Usage, and Sequestration (CCUS)	- Land areas directly impacted by the project, by ecosystem type (forests, cropland, grassland, wetlands, built-up land) - Change in the technology readiness level of a technology	- Section 8.12.2 Carbon sinks of the Tailored Impact Statement Guidelines Template. Source: https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/tailored-impact-statement-guidelines-projects-impact-assessment-act.html#toc50

			- Quantity of CO_2 sequestered	
		Others / in general	- Description of how the project will affect Canada's ability to meet its emissions reduction targets e.g. by replacing higher emitting activities - Explanation on how a project could impact global GHG emissions e.g., enabling the displacement of high-emitting energy abroad with lower emitting energy produced in Canada	- Section 8.12.3. Impact of the project on federal emissions reduction efforts and on global GHG emissions in the Tailored Impact Statement Guidelines Template. Source: https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/tailored-impact-statement-guidelines-projects-impact-assessment-act.html#toc50
Improve air quality	To minimize the emissions of other air pollutants generated by the marine sector e.g., SOx, NOx, volatile organic compounds	Design technologies (e.g., scrubber and engine) that allow vessels to go further below the sulfur cap of 0.1% within the North American Emission Control Areas and the IMO's requirements on nitrous oxide emissions	- Percentage reduction in NOx, SOx and PM emissions upon the adoption of technology - Percentage improvement in fuel efficiency and reduction in operational costs	- IMO's regulations on sulphur oxides, particulate matters and nitrogen oxides, available at: https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

		more effectively		
		Increase the uptake of lower-emissions fuels e.g., ultra low sulfur fuels	- Percentage reduction in NOx, SOx and PM emissions upon the adoption of alternative fuels	- Same as above
		Investigate impacts of low-carbon fuels on the generation of non-GHG air emissions	- Percentage change in emissions of air pollutants by switching fuel options	- The combustion of some alternative marine fuels could lead to air pollution e.g., combustion of ammonia may generate NOx. Source: https://www.sciencedirect.com/science/article/pii/S1540748918306345
		Design and implement measures that optimize operations to increase energy efficiency and reduce air pollutant emissions	- Energy Efficiency Operational Indicator (EEOI) - CO_2 emissions per unit of transport work or per ton-mile	- IMO's regulations on sulphur oxides, particulate matters and nitrogen oxides, available at: https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx
Improve water quality	To minimize the releases of chemical/pathogenic/biological contamination of concern	Develop technologies or management practices that minimize the occurrence and scale of oil spills, or improve the emergence response to an oil spill accident	- Estimated spill rate - Oil spill trajectories and probability of contact with an environmental resource - Combined probability of an oil spill occurring and contacting with an environmental resource - Volume and spatial area of oil spill	- More on the IMO's work on preventing oil spills and oil pollution is available at https://www.imo.org/en/OurWork/Environment/Pages/OilPollution-Default.aspx

			Source: https://www.boem.gov/environment/how-boem-calculates-oil-spill-risk	
		Develop technologies or management practices that reduce the amount of sewage and garbage produced by ships, or facilitate the treatment of sewage and garbage before the discharge from ships	- Weight or volume of expected sewage and garbage discharged	- The IMO has imposed regulations on the discharge of sewage and garbage. In general, ships engaged in international voyage, of 400 gross tonnage and above or which are certified to carry more than 15 persons, are required to be equipped with either an approved sewage treatment plant or an approved sewage comminuting and disinfecting system or a sewage holding tank. - The IMO also regulates the discharge of garbage, and only certain kinds of garbage could be discharged to the sea without any treatment. - Further details are available at: https://www.imo.org/en/OurWork/Environment/Pages/Sewage-Default.aspx https://www.imo.org/en/OurWork/Environment/Pages/Garbage-Default.aspx
		Develop technologies or management practices that reduce or process the discharge from pollution control devices e.g., scrubber	- Concentrations of concerned pollutants in the washwater or bleed-off water from scrubbers	- The washwater discharged by open-loop and hybrid scrubbers and the bleed-off water generated by close-loop scrubbers are contaminated with polycyclic aromatic hydrocarbons, particulate matter, nitrates, nitrites, and heavy metals, and it is often more acidic than the water into which it is discharged. These pollutants have been linked to cancer and reproductive dysfunction in marine mammals. Source: https://cleanshipping.org/wp-content/uploads/2024/03/MEPC-81-INF.36-Global-update-on-scrubber-EGCS-bans-and-restrictions-FOEI-WWF-Pacific-Enviro.1.pdf

Maintain shoreline/ sediment integrity	To maintain shoreline/sediment integrity	Advance technologies e.g., satellite remote sensing to better measure the extent of coastal erosion and its relationship with vessel wake	- Rate of coastal erosion - Estimation on whether vessel wake is exacerbating the erosion process	- Due to increasing permafrost melt from a warmer climate as well as decreasing amounts of sea ice that buffer coastlines against waves and storm surges, the rate and extent of coastal erosion is increasing throughout much of the Arctic which many Inuit, local communities and researchers continue to witness firsthand. Source: p.53 of https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf
		Propose measures e.g., nature-based solutions to mitigate coastal erosion and its impacts to the coastal communities	- Rate of coastal erosion - Avoided loss of economic values to coastal communities, or any other KPIs as appropriate for the communities	- Same as above
Mitigate underwater ocean noise	To reduce underwater ocean noise, defined as human-generated sounds that are transmitted beneath the surface of the water and have a wide range of impacts on marine animals	Advance technologies that could reduce underwater ocean noise	- Changes in underwater ocean noise	Details are available at Canada's Ocean Noise Strategy: https://www.dfo-mpo.gc.ca/oceans/publications/noise-bruit/strategy-strategie/index-eng.html#2-0
		Identify opportunities for vessel slowdown and route changes	- Description of how vessel slowdown, route changes and other interventions could reduce impacts of underwater ocean noise on species at risk.	
Others				
Biological environment				
Promote conservation and biodiversity	To reduce the negative impacts of vessel activities on species conservation and biodiversity	Minimize the occurrence and scale of spillage of fuels, including petroleum-based marine fuels and other alternative fuels.	- Changes in any risk assessment scores related to oil spills - Description regarding the emergency response to oil spills	- Source: p.52 of https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf - Biofuels such as biodiesel could also be subject to microbial contamination, and release of such fuel in the oceans in large quantities may have consequences (comment by workshop attendee)

		Develop emergency response protocols and technologies in the occurrence of spillage		
	To mitigate occurrence and the impacts of invasive species carried by vessel activities	Develop measures to prevent invasive species transferred via ships' ballast water	- Number of invasive species implicated, and their concentration in ballast water	- Came into force in 2017, the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) requires ships to manage their ballast water to remove, render harmless, or avoid the uptake or discharge of aquatic organisms and pathogens within ballast water and sediments. Details available at https://www.imo.org/en/MediaCentre/PressBriefings/Pages/21-BWM-EIF.aspx
		Develop measures to prevent invasive species transferred via ships' biofouling without harming the environment	- Number of invasive species implicated, and their concentration in ballast water	- The 2023 Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species (Biofouling Guidelines) (resolution MEPC.378(80)) are intended to provide a globally consistent approach to the management of biofouling, which is the accumulation of various aquatic organisms on ships' hulls. Source: https://www.imo.org/en/OurWork/Environment/Pages/Biofouling.aspx
	To reduce the negative impacts of vessel activities on fish and fish habitat	Develop measures to reduce the negative impacts of vessel activities on fish and fish habitat	- Changes in hydrological and hydrometric conditions and their effects on aquatic habitat and lifecycle activities (e.g., reproduction rearing, feeding, movements, migrations, winter refuge) and any changes to aquatic invertebrate communities - Risk of fish mortality	- Concerns regarding icebreaking activities' impacts on caribou can be found in p.51 of https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf - Section 8.8. Fish and fish habitat in the Tailored Impact Statement Guidelines Template. https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/tailored-impact-statement-guidelines-projects-impact-assessment-act.html#toc45

	To reduce the negative impacts of vessel activities on marine mammals	Reduce physical disturbance (e.g., strikes, icebreaking activities that might impede seasonal migration) on marine mammals	- Changes in sea ice conditions along the marine shipping routes	- https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf - Section 8.13 of the Tailored Impact Statement Guidelines Template. https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/tailored-impact-statement-guidelines-projects-impact-assessment-act.html#toc50
		Develop technologies (e.g., those related to propeller design) to reduce underwater noise, which could affect marine mammal distribution and behaviors, and marine mammal prey	- Changes in the exposure of various marine mammals to ship noise	- https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf
Others				
Socio-environment				
Respect Indigenous knowledge	To identify and understand the potential impacts of the research project on Indigenous peoples and their rights, including their lands, territories and resources, and to incorporate Indigenous knowledge with consent into the project	Engage with Indigenous groups, establish policies and stated principles related to the collection of traditional knowledge and traditional land use information for research purposes	- Description of the planned engagement methods or protocols, policies and principles	- Section 6. Description of Engagement with Indigenous Groups in the Tailored Impact Statement Guidelines Template. https://www.canada.ca/en/impact-assessment-agency/services/policy-guidance/practitioners-guide-impact-assessment-act/tailored-impact-statement-guidelines-projects-impact-assessment-act.html#toc22

Respect Indigenous marine uses (IMUs)	To understand the current and future pressures of vessel traffic on IMUs in each First Nations' territory, and to co-develop potential management recommendations that can be implemented to address adverse effects on IMUs, when and where necessary	Assess and mitigate the impacts of the project on shoreline harvesting, open-water harvesting, safe access to travel routes, and practicing cultural traditions by Indigenous communities	- Changes in the patterns of vessel traffic within an area of interest, such as amount of vessel transits, total residence time, distribution of traffic over time	- Source: p.37 of https://tc.canada.ca/sites/default/files/2023-03/tc_marineshipping_en.pdf
Facilitate equitable fisheries access and prosperity	To ensure the combination of fish harvesters' rights and capacities, that confer their ability to harvest and benefit from fisheries	Carry out studies to better understand the state of similarity or discrepancy regarding the level of fisheries access between fish harvesters and communities of different demographics (e.g., gender, age, Indigenous identity, education level, number of dependents, income, location) and how that could affect the benefits of fish harvesters	Types of access rights that fish harvesters can possess: - Right to enter and use an area - Right to harvest resources - Right to transfer rights to others - Right to prevent others from using a space or resources - Right to participate in the management of an area or resources Categories of assets that	- The mandates of Fisheries and Oceans Canada include sustainably managing fisheries as well as working with fishers, coastal and Indigenous communities to enable their continued prosperity from fish and seafood. More can be found on the website of Fisheries and Oceans Canada: https://www.dfo-mpo.gc.ca/about-notre-sujet/mandate-mandat-eng.htm - Research investigating the fisheries access in the Pacific Coast of Canada: https://doi.org/10.1016/j.marpol.2021.104581

		Develop policy tools to enhance equitable fisheries access in a sustainable way	support a fish harvester's capacity to access resources: - Financial assets such as capital, access to credit, subsidies and markets - Human assets such as education, skills, and labor - Social assets such as family supports, social capital, and community networks - Cultural assets such as local knowledge, community identity, and engagement in traditional practices - Physical assets such as boats, gear, infrastructure, and processing facilities - Political assets such as representation in decision-making processes, participation in management, and access to information	

Facilitate sustainable marine recreational activities	To allow marine recreation (i.e., activities, sports or games engaged in for leisure and enjoyment taking place in the marine environment) without harming the future use by others. Examples of marine recreation include recreational fishing, cruise ship travel, whale watching, diving, kayaking, sailing, and visiting beaches and other marine locations	Assess the magnitude, economic value and ecological impacts of marine recreational activities	- Extent of participation in marine recreational activities - Expenditure - Employment data - Number of species at risk affected, with description of how significant the impacts are	- Definition is adapted based on: https://publications.gc.ca/collections/collection_2010/mpo-dfo/Fs22-7-1-1-eng.pdf - Source of potential mechanisms: https://www.pewtrusts.org/-/media/legacy/uploadedfiles/peg/publications/report/pewossglobalbenefitspdf.pdf
		Develop targets and action items to integrate sustainable marine recreational activities effectively into comprehensive marine resource management plans	- Description of how sustainable marine recreational activities are incorporated into marine resources management plans (see additional context notes for an example)	While a guideline or action plan related to marine recreational activities is not available at the federal level, for reference, the BC Marine Recreation Action Plan (MRAP) targets five key goals: - Better understand the natural and cultural values of marine areas - Strengthen relationships with First Nations coastal communities - Provide high-quality marine recreation, today and in the future - Enhance collaboration with other government agencies - Promote ocean stewardship and responsible marine recreation Source: https://nrs.objectstore.gov.bc.ca/kuwyyf/MRAP_2d7821ccf5.pdf
Enhance climate adaptation and climate resilience	Adaptation refers to adjustments in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects. It refers to changes in processes, practices and structures to moderate potential	Develop Canadian-specific climate models that predict climate change impacts on water levels, flows, ice conditions, and extreme weather events	- Description of the research contribution to the state of knowledge or technology	- Source of definition: https://unfccc.int/topics/adaptation-and-resilience/the-big-picture/introduction - These potential mechanisms are summarized based on NRC Ocean program – Coastal resilience technology theme. Source: https://nrc.canada.ca/en/research-development/research-collaboration/programs/ocean-program-coastal-resilience-technology-theme
		Inform the development of nature-based solutions for flood and	- Description of the research contribution to the state of knowledge or technology	

	damages or to benefit from opportunities associated with climate change	erosion risk management		
		Develop reliable methods and tools to support the efficient renewal and future-proofing of existing marine infrastructure, and the sustainable design of new structures	- Description of the research contribution to the state of knowledge or technology	
Others				
Organizational alignment				
Align with the broader Government of Canada's strategies and values	To timely align with the priorities of the Government of Canada	Design specific evaluation criteria based on the strategic focus or priorities of the Government at the time	Specify how proposals can contribute to the current national or organizational priorities and strategies	- The National Shipbuilding Strategy as an example of the national and organizational priorities. https://www.canada.ca/en/public-services-procurement/services/acquisitions/defence-marine/national-shipbuilding-strategy/about.html
Align with the NRC's strategies and values	To timely align with the priorities of the National Research Council	Design specific evaluation criteria based on the strategic focus or priorities of the National Research Council at the time	Specify how proposals can contribute to the current national or organizational priorities and strategies	
Enhance organizational efficiency	To improve the operational effiency of the NRC and its ability to deliver impacts within certain time and capacity	Design specific evaluation criteria based on the internal operations of the NRC		
Ensure organizational continuity	To ensure the program generate revenue for sustainable and growing operations	Fund research projects that accelerate the implementation of clean technologies and develop a	- Change in Technology Readiness Level score - Projection on market uptake	

		clean tech market		
Others				
National security				
National security	To protect the safety and security of Canadians both at home and abroad, as well as Canadians' businesses and interests	Strengthen the resilience of Canada's vital assets and systems such as marine transportation, communications and public safety systems	- Description of how Canada's vital assets can remain undisturbed during critical events	- Details are available at Public Safety Canada https://www.publicsafety.gc.ca/cnt/ntnl-scrt/index-en.aspx
		Protect critical assets and information and combat cyber crime.	- Probability of cybercrime incidents - Description of improvement in preventive measures, catching potential breaches and emergency response	- Source: https://www.cyber.gc.ca/en/guidance/baseline-cyber-threat-assessment-cybercrime
		Develop energy independence throughtout the value chain	- Projected domestic supply and demand for different sources of energy	
		Anticipate future technical skills and prepare workforce for these needs	- Description of the skills, job opportunities and their corresponding income levels	
Others				
Well-being of mariners and maritime professionals				
Mariner safety	To ensure the well-being and security of those working on a vessel	Understand crew safety at various nodes of the hazard identification (HAZID) process under different	- Number of high, medium and low risks in a HAZID assessment	- More novel alternative fuels and technologies require specific safety protocols and training and monitoring (workshop participant)

		operation scenarios		
		Develop navigational support systems	- Description of the research contribution to the state of knowledge or technology	
Mariner habitability	To ensure acceptability of the conditions of a vessel in terms of whole-body vibration, noise, indoor climate, and lighting, as well as physical and spatial characteristics, according to prevailing research and standards for human efficiency and comfort	Design comfortable work environments and operational work profiles	- Accommodation area for mariners - Level of whole-body vibration during vessel operations - Intensity of sound produced by propulsion systems and onboard equipment	- The ABS Guide for Habitability of Industrial Personnel on Accommodation Vessels defines mariner habitability and establishes criteria for improving the living environment and ambient environment on board accommodation vessels. Source: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/guide_habitability_industrial_personnel_accommodation_vessels/HAB_ACCOM_Guide_e-Jan17.pdf
Others				
Social equity and inclusiveness				
Stakeholder engagement and inclusiveness	To engage a wide range of stakeholders and ensure that the concerns and values of various stakeholder groups are taken into account when identifying research areas or projects to support	Engage diverse stakeholder groups in problem definition and solution aspects	- Stakeholder mapping and description of engagement methods	
Knowledge generation and mobilization	To enhance the sharing and uptake of information across governmental agencies,	Create platforms or tools that different stakeholders can co-operate to generate	- Description of parties involved (e.g., other research institutions, NGOs, schools) in the	

	businesses, and/or with broader society	and share knowledge	knowledge co-creation platforms, and the mechanisms	
		Involve the public in the research process e.g., citizen science	- Number of citizens engaged in the research process, and where available, their demographic information	
		Share the research knowledge with the public to increase their awareness of certain topics	- Description of stakeholder engagement channels - Number of citizens engaged - Survey feedback collected from participants	
Canadian workforce and capabilities				
Build resilient Canadian workforce and capabilitie s	To build Canadian workforce and capabilities that could bring economic prosperity in the present and future	Facilitate industry growth, creating job opportunities	- Estimated number of jobs to be created	
		Develop high-skilled future workforce by training graduate students	- Estimated number of jobs to be created	
		Work with SMEs	- Estimated numbers of SMEs that could benefit from the project, with description	

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