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«ENGINEERING - ECONOMIC SYSTEMS»

MASTER'S THESIS

SUSTAINABILITY OF ALTERNATIVE MARINE FUELS:

EXTENDED VIKOR METHOD USING INCOMPLETE INFORMATION CRITERIA WEIGHTS

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Περιληπτικό Απόσπασμα

Η προσαρμογή της Συμφωνίας του Παρισιού το 2015 και οι δεσμεύσεις που ακολούθησαν την αρχική πράξη, εκφράζουν απόλυτα την ευαισθησία της παγκόσμιας κοινότητας σε θέματα που αφορούν τις δράσεις για το κλίμα και την αντιμετώπιση των επιπτώσεων της υπερθέρμανσης του πλανήτη. Η υλοποίηση των στόχων που τέθηκαν από τη σύμβαση-πλαίσιο των Ηνωμένων Εθνών για τις κλιματικές μεταβολές (UNFCCC) απαιτεί τον εκτεταμένο επανασχεδιασμό των ενεργειακών συστημάτων, της ναυτιλίας, των μεταφορών και της κατανάλωσης ενέργειας, τα οποία επηρεάζουν το μεγαλύτερο μέρος της ανθρώπινης δραστηριότητας και μετασχηματίζουν τη συμπεριφορά των καταναλωτών παγκοσμίως.

Οι παγκόσμιες σωρευτικές προσπάθειες εδραίωσαν τη σημασία της στοχοθέτησης για μηδενικές ανθρωπογενείς εκπομπές έως το 2050. Στο πλαίσιο αυτό, ο διεθνής ρυθμιστικός φορέας της ναυτιλίας IMO (Διεθνής Ναυτιλιακός Οργανισμός) έχει θέσει ως στόχο τη μείωση των εκπομπών αερίων του θερμοκηπίου[1] κατά 50% έως το 2050, επιδιώκοντας παράλληλα μείωση της πυκνότητας εκπομπών άνθρακα ανά μεταφορικό έργο κατά τουλάχιστον 40% έως το 2030, στοχεύοντας σε μείωση κατά 70% έως το 2050. Για την επίτευξη αυτών των στόχων, ο IMO εισήγαγε μια τεχνική απαίτηση - τον Δείκτη Ενεργειακής Απόδοσης Υφιστάμενων Πλοίων (EEXI) - στον υφιστάμενο ενεργό στόλο και μια ανάλογη απαίτηση κατά τη φάση σχεδιασμού των νεόδμητων πλοίων, τον Δείκτη Σχεδιασμού Ενεργειακής Απόδοσης (EEDI). Η δεύτερη νομοθετική πράξη επικεντρώνεται στην επιχειρησιακή αξιοποίηση του παγκόσμιου στόλου μέσω ενός επιτευχθέντος ετήσιου επιχειρησιακού δείκτη έντασης άνθρακα, γνωστού ως Δείκτη Έντασης Άνθρακα (CII). Παράλληλα, η πρόταση για επέκταση του πεδίου εφαρμογής του συστήματος εμπορίας εκπομπών της ΕΕ ώστε να καλύπτει τις θαλάσσιες μεταφορές, διατυπώθηκε και επικυρώθηκε σε σύνοδο της ολομέλειας του Ευρωπαϊκού Κοινοβουλίου νωρίτερα αυτό το καλοκαίρι.

Η ραγδαία εξέλιξη των ρυθμιστικών συνομιλιών, με στόχο την επιτάχυνση της ενεργειακής μετάβασης του κλάδου, δημιουργεί αυξανόμενο ενδιαφέρον για μοντελοποίηση και αξιολόγηση εναλλακτικών ενεργειακών οδών στη ναυτιλία. Ακολουθώντας αυτή την τάση, πολλά ενδιαφερόμενα μέρη έχουν ξεκινήσει την σχεδίαση πλαισίων και μεθοδολογιών αξιολόγησης του κύκλου ζωής των εκπομπών των εναλλακτικών πηγών καυσίμου, καθώς παράλληλα έχουν εδραιώσει ευρείες συνεργασίες για τη διερεύνηση και την ανάπτυξη νέων αλυσίδων εφοδιασμού για τις εναλλακτικές πηγές ενέργειας. Στο πλαίσιο αυτό, οι εναλλακτικές λύσεις καυσίμων αξιολογούνται βάσει διαφόρων κριτηρίων βιωσιμότητας σε βραχυπρόθεσμο, μεσοπρόθεσμο και μακροπρόθεσμο ορίζοντα. Για την αντιμετώπιση αυτού του πολυπαραμετρικού προβλήματος, έχει επιλεγεί η χρήση πολυκριτηριακών μεθόδων υποστήριξης αποφάσεων (MCDM) , ως ένας αποτελεσματικός τρόπος καθοδήγησης των υπευθύνων για τη λήψη αποφάσεων, παρέχοντας παράλληλα και μια εξελιγμένη διαδικασία επιλογής. Αξιοποιώντας ελλιπείς πληροφορίες σχετικά με τη βαρύτητα των κριτηρίων, εξετάζονται διαφορετικά σενάρια σύμφωνα με την εκτεταμένη μεθοδολογία VIKOR για την αξιολόγηση της μεσοπρόθεσμης και μακροπρόθεσμης βιωσιμότητας των εναλλακτικών καυσίμων πλοίων. Η μελέτη επικεντρώνεται σε τρεις κύριες κατηγορίες καυσίμων. Πιο συγκεκριμένα, εξετάζονται οι εναλλακτικές λύσεις καυσίμων βιολογικής προέλευσης, όπως είναι το βιοντίζελ, το υγροποιημένο βιοαέριο / βιο-LNG και η βιομεθανόλη, τα συνθετικά καύσιμα με βάση τον άνθρακα, όπως είναι

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[1] Πηγή: Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG emissions in the shipping sector, MEPC 72, 2018

η ηλεκτρονική μεθανόλη και το ηλεκτρονικό μεθάνιο, μαζί με τις εναλλακτικές λύσεις που δεν βασίζονται στον άνθρακα, όπως είναι το υγροποιημένο πράσινο υδρογόνου και η συνθετική αμμωνία. Τα κριτήρια καλύπτουν ένα ευρύ φάσμα, συμπεριλαμβανομένων των οικονομικών, περιβαλλοντικών επιδόσεων, καθώς και μετρικών που σχετίζονται με την ασφάλεια και την κοινωνική αποδοχή των εναλλακτικών λύσεων. Βάσει του πλαισίου στάθμισης των κριτηρίων με χρήση ασθενών ανισοτήτων, προκύπτει η συμβιβαστική λύση ή το σύνολο συμβιβαστικών λύσεων. Διερευνώντας διαφορετικά σενάρια στάθμισης κριτηρίων, εξετάζεται η ευρωστία της επιλογής μαζί με την πιθανή σύγκλιση των σεναρίων και την ευαισθησία της διαδικασίας λήψης αποφάσεων στη συγκεκριμένη εφαρμογή.

Abstract

The adaptation of the Paris Agreement in 2015 and the pledges following the initial act, have captivated the appeal of global community to recognize the importance of climate action and address the growing concern over the effects of global warming. Actualizing the targets set by the United Nations Framework Convention on Climate Change (UNFCCC), require vast redesigning of energy systems, shipping, transport, and energy consumption affecting most of the human activity and transforming consumers behaviour worldwide.

Global cumulative efforts solidified the importance of reaching net zero emissions by 2050. In this respect, the international regulatory body of shipping IMO (International Maritime Organisation) has set the target[i] of cutting GHG emissions by 50%[2] by 2050 while pursuing a reduction on carbon intensity per transport work by at least 40% by 2030, targeting a 70% reduction by 2050. To achieve these targets, IMO introduced a technical requirement, namely Energy Efficiency Existing Ship Index (EEXI), to the existing active fleet and a similar requirement at the design phase of newly built vessels, the Energy Efficiency Design Index (EEDI). The second legislative act focuses on operational utilization of the global fleet through an attained annual operational carbon intensity indicator, known as Carbon Intensity Index (CII). In parallel, the proposal to extend the scope of the EU's Emissions Trading System to cover maritime transport, has been adopted at a plenary session of European parliament earlier this summer.

The rapid development on regulatory talks, targeting the acceleration of the sector's energy transition, creates a growing interest in modelling and evaluation of alternative pathways in shipping. Going down that path, many stakeholders have initiated evaluation frameworks, life cycle assessment methodologies and broad coalitions on exploring and developing supply and value chains for alternative energy sources. In this scope, fuel alternatives are evaluated under several sustainability criteria for their short-, mid- and long-term potential. To address this multi-parametric problem, a multi-criteria decision making (MCDM) framework has been selected, at this study, as an effective way to navigate decision makers and provide a sophisticated selection process. By utilizing incomplete information on criteria weights, different scenarios are evaluated under the extended VIKOR methodology to assess the mid- and long-term sustainability of marine alternative fuels. The study focuses on three main categories of fuels. The bio-origin fuel alternatives, biodiesel, liquified biogas/ bio-LNG and bio methanol; the synthetic carbon-based fuels, e-methanol, and e-methane, along with the non-carbon-based alternatives of liquified green hydrogen and the synthetic ammonia. The criteria cover a broad range of aspects, including economic, environmental, safety and social performance of the alternatives, under the weak inequalities' criteria weights framework, to conclude to the compromise solution or set of solutions. Exploring different criteria weighting scenarios, the robustness of selection is examined along with the convergence potential and the sensitivity of the decision-making process at this particular application.

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[2] Source: Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG emissions in the shipping sector, MEPC 72, 2018

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Climate Actions: Global Warming Targets and Trajectories

International community has recognized the importance of climate action, as the effects of global warming are now more evident. Within this scope, the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement in 2015 (United Nations Climate Change, 2015), pledging to take on increasingly ambitious targets aimed at stabilising and then sharply reducing Greenhouse Gas (GHG) emissions. To stay in line with the Paris Climate Agreement Goals average global temperature rise is to be limited to below 2° C, while the stretch target is to limit the increase in average global temperatures to 1.5 °C, against the pre-industrial levels. Fulfilling this target requires focusing all efforts towards reaching net zero emissions by 2050 and necessitates a complete transformation of energy production, consumers behaviour, shipping, transport, and energy consumption affecting the majority of human activity worldwide.

During COP26 (United Nations Climate Action, 2021), concluded in November 2021, where almost 200 countries were represented, an agreement has been achieved on the roadmap of climate action and the global goals of accelerating action on climate this decade, materialised by issuing the Glasgow Climate Pact. The agreement and the pledges made, have the objective of limiting the rise in global temperature, creating the framework required by the Paris Rulebook. The agreement is based on four main pillars.

The Nationally Determined Contributions (NDCs) and the commitments made (United Nations Climate Action, 2021) cover 90% of world GDP, with many countries putting forward new emissions targets for 2030. To deliver on these stretching targets, commitments from representatives were made to move away from coal power, the most harmful energy source in terms of climate impact. To manage consumption of carbon intensive energy sources, focus has been given in switching energy tense industries and human activities to electrification and cleaner energy supply. The acceleration of the uptake on electric vehicles was agreed, as transport is one of the sectors consuming high percentage of total energy consumption as shown at Figure 1 and is heavily relying of fossil fuels. Limiting deforestation and gradually reversing the trend was also agreed in principle, while a new objective on reduction methane emissions was raised.

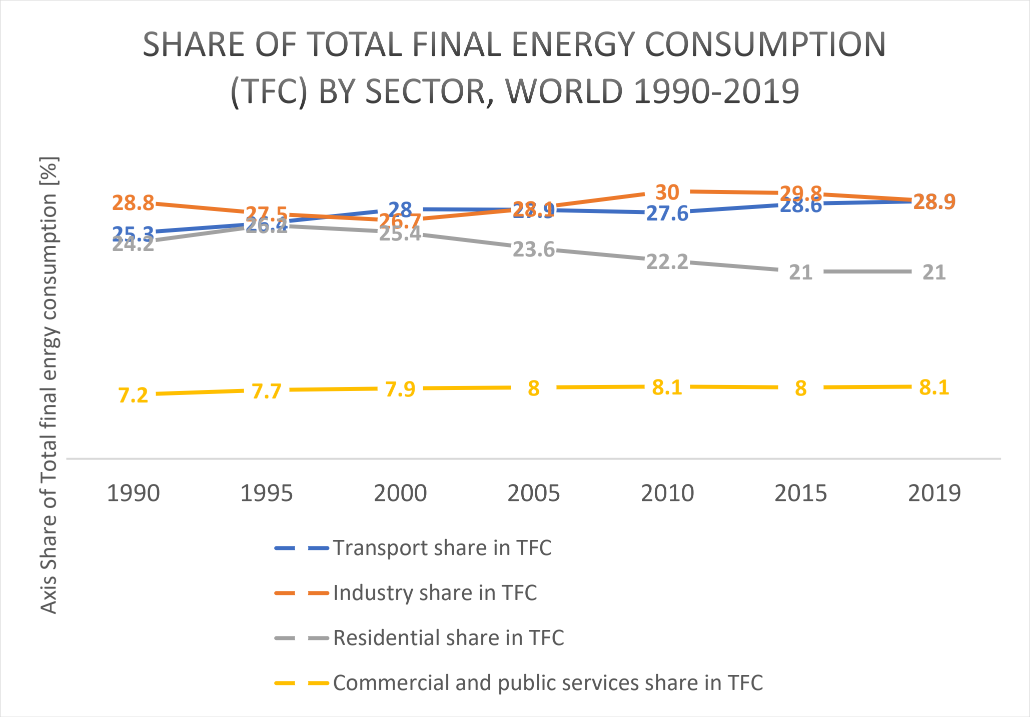

Figure 1: Share of total final energy consumption (TFC) by sector

Source: IEA Energy and Carbon Tracker (2020)

Adaptation actions and increased preparedness against climate risks on global level have been discussed, strengthening effort to deal with climate impacts, resulting in the Adaptation Communications or National Adaptation Plans covering 80 countries from which, 45 plans were submitted over the last year. Commitment to doubling adaptation finance by 2025 compared to 2019 budget is considered a milestone as for the first time, specific financing goal has been agreed globally. To narrow the financial gap, access to finance and partnerships between countries is essential in global efforts to mitigate the differences between developed and developing countries.

Financial transition is recognized as an essential target. Developed countries have made progress towards a $100 billion climate finance goal which, according to the initial planning, this target is to be reached by 2023. In respect to this, vital fund structures have been developed, such as the Least Developed Countries Fund, to support the transition in countries lacking the financial access. As the target is global, tackling climate risks is only effective when all countries have the necessary tools available. During the last COP meeting, 34 countries and five public finance institutions have decided to limit international support for the unabated fossil fuel energy sector in the years to come, which essentially is redirecting investment of the energy sector to cleaner modes. In a similar scope, private financial institutions, central banks, and individual investors, through Environmental Social and Governance (ESG) indexing, are moving to realign funds at the range of trillions of dollars towards global net zero emissions.

Collaborative work between governmental entities, public and private businesses and society will help delivering on climate commitments and pledges. Critical for such collaboration is the agreed framework. At COP26, in continuation to the Paris Rulebook, a common reporting system of emissions has been agreed, providing a new mechanism for standardisation of international carbon markets assessing climate impact and providing timeframes for emissions reductions targets.

Decarbonisation of the Shipping Sector

Global cumulative efforts solidified the importance of reaching net zero emissions by 2050. In this respect, the international regulatory body of international shipping IMO (International Maritime Organisation) has set the target of cutting GHG emissions by 50% by 2050, while pursuing a reduction on carbon intensity per transport work by at least 40% by 2030, targeting a 70% reduction by 2050. However, the targets set by IMO fall short at the full decarbonisation of the sector by 2050. Thus, international agencies (IEA, 2021) have issued reports highlighting the importance of additional policies to reduce carbon intensity of shipping activities and further incentivise the adoption of low- and zero-carbon fuels, while developing the technologies for oceangoing vessels.

Identifying this regulatory gap, the international community, during COP26, urged shipping community to accelerate efforts through the Declaration on Zero Emission Shipping, which calls on the International Maritime Organisation to align its targets with full decarbonisation by 2050.

The declaration, signed by 15 member states, requests IMO to regulate more strictly greenhouse gas emissions and ensure that the regulatory framework facilitates decarbonisation initiatives in the industry. The declaration highlights the importance of broad international collaborations from all members of the value chain, both on a governmental and private level, to develop new green technologies and to ensure that a critical mass of zero-emission ships is on the water by 2030, placing shipping on the required pathway to full decarbonization by 2050, while adopting the short, mid and long term measures to help achieve this goal (COP26, 2021).

Regulations of the International Maritime Organisation

The current commitment of IMO addressing the climate change is illustrated by the implementation of Sustainable Development Goals, while the initial IMO strategy on reduction of greenhouse gas emissions was adopted in April 2018, providing the targets mentioned on the reduction of carbon intensity per transport work and the total greenhouse gas emissions by 2050.

Marine Environment Protection Committees (MEPC) is the broader legislative body of IMO, which incorporated all emissions and climate related aspects of the regulations, providing the guidelines to the global shipping community. The first mandatory measure for climate mitigation was introduced ten years ago, and all the efforts have been developed and adopted through the years, through this framework. In June 2021, MEPC 76 adopted measures and provided short-term targets for the reduction of carbon intensity. This was done through two different legislative acts.

Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI)

The first one focuses on the technical aspects of the active fleet and the vessels to be built in the current decade. This measure introduces new requirements on the energy efficiency certificate of all vessels, through an index, the Energy Efficiency Design Index (EEDI) or the Energy Efficiency Existing Ship Index for the currently active vessels.

Starting for the vessels under construction and the future orders, an energy efficiency improvement on the designed operational point is required. Essentially, the measure focuses on the carbon emissions at the maximum summer load line per nautical mile, thus the carbon emissions at the maximum design transport work. This regulation was introduced in different phases, with gradually stricter requirements, per vessel type, against a reference value per vessel segment provided by IMO (MEPC.328(76), 2021). Table 1 provides the reduction factors for the EEDI against the reference for each phase and the provided timeline.

Ship Type	Size	"Phase 0" 1 Jan 2013 -31 Dec 2014	"Phase 1" 1 Jan 2015 - 31 Dec 2019	"Phase 2" 1 Jan 2020 -31 Mar 2022	"Phase 2" 1 Jan 2020 -31 Dec 2024	"Phase 3" 1 Apr 2022 and onwards	"Phase 3" 1 Jan 2025 and onwards
Bulk carrier	20,000 DWT and above	0	10		20		30
	10,000 and above but less than 20,000 DWT	n/a	0-10		0-20		0-30
Gas Carrier	15,000 DWT and above	0	10	20		30	
	10,000 and above but less than 15,000 DWT	0	10		20		30
	2,000 and above but less than 10,000 DWT	n/a	0-10		0-20		0-30
Tanker	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 20,000 DWT	n/a	0-10		0-20		0-30
Containership	200,000 DWT and above	0	10	20		50	
	120,000 and above but less than 200,000 DWT	0	10	20		45	
	80,000 and above but less than 120,000 DWT	0	10	20		40	
	40,000 and above but less than 80,000 DWT	0	10	20		35	
	15,000 and above but less than 40,000 DWT	0	10	20		30	
	10,000 and above but less than 15,000 DWT	n/a	0-10	0-20		15-30	
General cargo ships	15,000 DWT and above	0	10	15		30	
	3,000 and above but less than 15,000 DWT	n/a	0-10	0-15		0-30	
Refrigerated cargo carrier	5,000 DWT and above	0	10		15		30

	3,000 and above but less than 5,000 DWT	n/a	0-10		0-15		0-30
Combination carrier	20,000 DWT and above	0	10		20		30
	4,000 and above but less than 20,000 DWT	n/a	0-10		0-20		0-30
LNG carrier	10,000 DWT and above	n/a	10	20		30	
Ro-Ro cargo ship (vehicle carrier)	10,000 DWT and above	n/a	5		15		30
Ro-Ro cargo ship	2,000 DWT and above	n/a	5		20		30
	1,000 and above but less than 2,000 DWT	n/a	0-5		0-20		0-30
Cruise passenger ship (having non-conventional propulsion)	85,000 GT and above	n/a	5	20		30	
	25,000 and above but less than 85,000 GT	n/a	0-5	0-20		0-30	

Table 1 : Reduction factors (in percentage) for the EEDI relative to the EEDI reference line (MEPC.328(76), 2021)

The reference lines are provided in the same regulations. An exponential equation is used for calculating the reference while the parameters of the equation depend on the category and deadweight (DWT) of each ship.

Similarly, the Energy Efficiency Existing Ship Index for the currently active vessels (EEXI), is a fixed reduction of carbon intensity per transport work for each vessel type against the EEDI reference. This index is calculated in the same way as EEDI, but the reduction factor is fixed and need to be implemented on all vessels requiring a corrective action to technically limit carbon intensity at the design condition. The table below provides the reduction factor against the EEDI reference for each ship type (MEPC.328(76), 2021).

Ship Type	Size	Reduction factor
Bulk carrier	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	10,000 and above but less than 20,000 DWT	0-20
Gas Carrier	15,000 DWT and above	30
	10,000 and above but less than 15,000 DWT	20
	2,000 and above but less than 10,000 DWT	0-20
Tanker	200,000 DWT and above	15
	20,000 and above but less than 200,000 DWT	20
	4,000 and above but less than 20,000 DWT	0-20
Containership	200,000 DWT and above	50
	120,000 and above but less than 200,000 DWT	45
	80,000 and above but less than 120,000 DWT	35
	40,000 and above but less than 80,000 DWT	30
	15,000 and above but less than 40,000 DWT	20
	10,000 and above but less than 15,000 DWT	0-20

General cargo ships	15,000 DWT and above	30
	3,000 and above but less than 15,000 DWT	0-30
Refrigerated cargo carrier	5,000 DWT and above	15
	3,000 and above but less than 5,000 DWT	0-15
Combination carrier	20,000 DWT and above	20
	4,000 and above but less than 20,000 DWT	0-20
LNG carrier	10,000 DWT and above	30
Ro-Ro cargo ship (vehicle carrier)	10,000 DWT and above	15
Ro-Ro cargo ship	2,000 DWT and above	5
	1,000 and above but less than 2,000 DWT	0-5
Cruise passenger ship (having non-conventional propulsion)	85,000 GT and above	30
	25,000 and above but less than 85,000 GT	0-30

Table 2: Reduction factors (in percentage) for the EEXI relative to the EEDI reference line (MEPC.328(76), 2021)

Vessels impacted by EEXI, meaning the vessels whose EEXI score do not meet the expected reduction against the reference, must demonstrate compliance by their next survey – annual, intermediate or renewal – for the International Air Pollution Prevention Certificate (IAPPC), or the initial survey before the ship enters service for the International Energy Efficiency Certificate (IEEC) to be issued, whichever is the first on or after 1 January 2023.

Carbon Intensity Index (CII)

The second legislative act focuses on operational utilization of the global fleet through an attained annual operational carbon intensity indicator, known as Carbon Intensity Index (CII). Starting from 2023, after the end of each calendar year the annual operational CII shall be calculated over a 12-month period from 1 January to 31 December for the preceding calendar year, using the data collected in accordance with the framework provided under the regulation 27 of MARPOL Annex VI, on the collection and reporting of ship fuel oil consumption data. Similarly with the technical indexes, IMO developed the required annual operational carbon intensity indicator references per vessel category. The rolling target, with stricter requirements against the reference for each year to ensure continuous improvement, is now agreed to be 2% improved per year till 2026. Within the current framework, each vessel is to be assigned with an energy efficiency rating per year.

The attained annual operational CII is to be documented after being verified against the required annual operational CII target to determine an operational carbon intensity rating A, B, C, D or E indicating a major superior, minor superior, moderate, minor inferior, or inferior performance level, respectively.

Based on this rating, corrective actions are required for ships rated as D for three consecutive years or rated as E, for one year. A plan for corrective actions to achieve acceptable rating in the future is required and the Ship Energy Efficiency Management Plan (SEEMP) shall be reviewed to reflect the plan of corrective actions.

IMO, as the global regulatory body in shipping, develops a binding framework that applies to the world fleet and is enforced globally, providing equal terms without distorting any specific trade flow, as it may happen through regional legislations. The global framework provides assurance that carbon leakage is avoided and that the risk of sub-optimal shipping in certain parts of the world is avoided. However, Member

States are encouraged, within the IMO framework, to take action to develop and update voluntary National Action Plans (NAP) with a view to contributing to reducing GHG emissions from international shipping by supporting actions at national level.

European Union Regional Legislation in the Context of "Fit for 55" – European Green Deal

The regional imbalance of the political act on climate, has resulted in the development of regional regulation or preferably, initiated discussion on an accelerated action plan compared to the IMO framework.

European Union has published its update to the green deal, known as "Fit for 55" in reference to the 55% reduction in carbon emissions targeted for 2030. The proposals are intended to enable the acceleration of greenhouse gas emission reductions in the next decade, including shipping, with a combined set of measures (European Commission, 2021).

Firstly, the inclusion of shipping at the existing EU Emissions Trading System (ETS) was introduced, while in parallel, tightening of the existing EU Emissions Trading System (ETS) for all sectors.

The second target of European Union, which is reflected in the legislative work done, is to increase the use of renewable energy, enhance greater energy efficiency and accelerate the uptake of low emission transport modes. In this scope, the EU fuel Maritime Regulation was developed and introduced into the discussion.

To achieve those goals, dedicated EU funds and incentives have been developed to create the infrastructure and fuels supply chain to support this accelerated transition, supported by an alignment of taxation policies with the European Green Deal objectives; measures to prevent carbon leakage; and tools to preserve and grow the natural carbon sinks.

Emission Trading System (EU-ETS)

EU ETS is the largest emissions trading system across multiple countries and multiple sectors, established by the European Union in 2005. It provides a regulated system of trading emissions credits across organisations, with a maximum number of allowances available for purchase, within the scheme's limits. Free allowances are distributed to sectors based on their maturity to support a realistic transition to low carbon economy. Initial auctioning for all sectors is the primary market for obtaining carbon allowances, however, allowances are available, subject to trade, on a secondary market. Thus, the price of the carbon allowance is decided based on the supply and demand law of the market.

The latest proposal, released on 14 July 2021, extends the scope of the EU's Emissions Trading System to cover maritime transport. As described in the proposal, EU ETS is to be applicable for the emissions under voyages within European Union, including any emissions occurring at berth in any port under the jurisdiction of EU and half of the emissions of any voyage which includes an EU port, either as port of departure or port of arrival. The obligation to surrender allowances in the maritime transport sector is gradually phased-in over the period 2023 to 2025, with shipping companies having to surrender 100% of their verified emissions as of 2026 (European Commission, 2021). The monitoring and reporting rules, as well as verification and accreditation rules laid out shall be following the Regulation (EU) 2015/757, which is an older legislation on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, similar but not the same as IMO's Data Collection System (regulation 27 of MARPOL Annex VI).

The target of EU ETS is rolling, following a linear reduction factor of 4,2 % from the year following the entry into force of this Directive amending the ETS Directive. The increased linear reduction factor is combined with a one-off downward adjustment of the cap so the new linear reduction factor has the same effect as if it would have applied from 2021. This ensures that the overall quantity of allowances ('cap') will decline at an increased annual pace resulting in an overall emission reduction of sectors under the EU ETS of 61% by 2030 compared to 2005. In addition, from the year following entry into force of this Directive, the cap is to be increased by the number of allowances corresponding to the maritime transport emissions derived from data from the EU Maritime transport Monitoring Reporting and Verification system for the years 2018 and 2019, adjusted, from year 2021, by the linear reduction factor.

The proposal suggests a phase-in plan for maritime transport, in which Shipping companies (ongoing discussions to extend liability to commercial operator) shall be liable to surrender allowances according to the following schedule[3]:

20% of verified emissions reported for 2023

45% of verified emissions reported for 2024

70% of verified emissions reported for 2025

100% of verified emissions reported for 2026 and each year thereafter.

Non-compliance with the EU ETS scheme shall have considerable implications on the company's assets and business operations. Shipping companies failing to surrender allowances for two or more consecutive reporting periods, could face an expulsion order against the ships under their management. This could lead in assets being detained by the Member State the ship is flagged in (for the ships/assets flagged under a Member State) or denied entry into a port under the jurisdiction of a Member State.

Similar schemes have been introduced in other regions, such as the United Kingdom, having its own independent emissions trading system, known as UK ETS. Review of the current proposal by the European Commission is to be considered in the case of the adoption by the IMO of a similar market-based measure to reduce greenhouse gas emissions from maritime transport, achieving the goals set by EU on the trajectory of the accelerated emissions reduction and decarbonisation of the sector.

Fuel EU Maritime

Maritime transport is an essential component of European Union's trade, responsible for most of the EU's external trade and contributing significantly to EU's internal trade, proving critical for the economic prosperity of the region. As maritime transport is an

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[3] (European Commission, 2021)

international service network, not bound to EU shipowners and operators, a level playing field is essential. This fact is recognised by the European regulators and is reflected in all attempts to regulate the industry. The EU 2030 Climate Target regarding shipping sector is founded in two basic components. Energy efficiency improvement, which is mainly addressed under the macro perspective approach of EU-ETS, followed by the uptake of cleaner types of fuels, which is addressed through the Fuel EU Maritime proposal.

Currently, the maritime sector relies almost entirely on fossil fuels. Through the Climate Target Plan (European Commission, 2021), the goal is to increase the renewable share of fuels in the sector and to develop electrification facilities, providing the option of supply of shore power. In parallel it encourages the uptake of advanced biofuels and other renewable and low carbon fuels, focusing on a hydrogen based synthetic fuel future market structure, which is evaluated as critical for the decarbonisation of energy intensive, hard to abate sectors, such as shipping and aviation.

The Fuel EU Maritime initiative (European Commission, 2021) proposes a common EU regulatory framework to increase the share of renewable and low-carbon fuels in the fuel mix, while trying to minimize the effect that such regulation could have at a regional level avoiding the creation of barriers to the EU market. Distortion of the global competitiveness between operators flagged in different countries, active on different trading routes and diversion of trade routes are particularly relevant to fuel requirements since fuel costs is a substantial share of ship operators' costs. Indicatively, dependent on the fuel prices and operating speeds fuel costs could make up to around 35% of the freight rate of a small, low speed vessels to around 55% for high-speed trades (e.g. containerships). As a result, any regional variation in fuel prices could significantly affect the profitability of operators, pushing them on other trade routes.

To effectively apply measures on all the activities of the maritime transport sector, the target of the regulatory proposal in question, covers a share of the voyages between a port under the jurisdiction of a Member State and port under the jurisdiction of a third country, similarly with EU ETS. Namely, it applies to half of the energy used by a ship performing voyages arriving at a port under the jurisdiction of a Member State from a port outside the jurisdiction of a Member State and half of the of the energy used by a ship performing voyages departing from a port under the jurisdiction of a Member State and arriving at a port outside the jurisdiction of a Member State. The entirety of the energy used by a ship performing voyages between ports under the jurisdiction of Member States is being considered. Lastly, the energy used at berth in a port under the jurisdiction of a Member State is fully considered as energy consumption under the Fuel EU Maritime scheme. As such regulation is limited to specific trading routes and creates concerns on regional level, Commission is to review this regulation in view of aligning it to the international rules when consensus is reached in a global approach regarding the matter.

Measuring environmental performance of various energy sources, potentially applicable to shipping, the proposed policy framework, follows the "well-to-wake" approach as it considers all emissions, including the combustion of fuel on board the ship, the upstream emissions from production, transport, and distribution of fuels. The target is to establish the methodology and the formula that should apply to calculate the yearly average greenhouse gas intensity of the energy used on-board by a ship. In this respect, a verification process and certification of alternative fuels and their environmental performance is being developed under the (Directive (EU) 2018/2001, 2018).

The greenhouse gas intensity of the energy used on-board by a ship is calculated in terms of grams of carbon dioxide equivalent (other pollutants are also being considered) per MJ of energy.

A reference is to be selected, based on the current greenhouse gas intensity of the energy sources used onboard with the regulation providing concrete targets of gradual reduction, per year according to the below percentages (European Commission, 2021):

-2% from 1 January 2025

-6% from 1 January 2030

-13% from 1 January 2035

-26% from 1 January 2040

-59% from 1 January 2045

-75% from 1 January 2050 onwards.

Managing compliance balanced has created a relatively complex framework. Any compliance surplus for any reporting period exceeding the targets of the regulation, could be used at the same ship's compliance balance for the following reporting period. Similarly, when a ship has a compliance deficit for any reporting period, the responsible party has the option to borrow an advance compliance surplus of the corresponding amount from the following reporting period. However, this is done with a penalty as the deducted compliance balance required is multiplied by 1.1. Requirements for the advance compliance surplus should not exceed 2% of the limit and this procedure cannot be followed for two consecutive reporting periods.

Another option provided by the proposed regulation to achieve compliance is by pooling fleets of two or more vessels verified by the same verifier. Company or companies involved in the pool have the flexibility to decide how to allocate the total compliance balance of the pool to each individual ship, provided that the total pool compliance balance is respected. If the compliance balance is not met, a penalty is issued. The detailed methodology of calculating greenhouse gas intensity balances and the penalties arising from non-compliance are presented in detail at (European Commission, 2021).

This mosaic of regulations and the various timeline of all legislative bodies have created a complex environment for developing the strategy to commit and achieve the short–term, mid–term, and long–term targets.

Recognizing the overall challenge, many organisations have developed an initial pathway for the carbon reduction strategies, identifying gaps for meeting the mid-term and long-term goals, and driving the change at the maritime sector as it enters the era of energy transition and decarbonisation.

Several alternative or renewable fuels with lower carbon content than conventional fuels are being considered for power generation and propulsion for the reduction of GHG emissions.

Uptake of those alternatives requires consideration regarding many aspects. Technological complexity, application experience, available fuel options, current and future regulatory requirements, and safety concerns are to be reviewed and developed to create the sufficient environment for the gradual adoption of those fuels. The evaluation of the GHG impact is a complicated issue. The requirements differ among the proposed regulations and the legislations in place. Some encompass the total emissions accounted from the "well-to-wake" lifecycle emissions, while others focus on the impact of "tank-to-wake" that is directly linked to the vessels' power generation and propulsion. Increased interest has been shown lately for carbon capture technology either as a supplemental solution or a mid-term solution for reducing a vessel's overall carbon footprint.

Literature Review

The modelling and evaluation of alternative pathways is an important task for the entire energy sector, as the development of sustainable energy systems and the design of the future energy mix have many underlining challenges. Energy security and affordability of resources need to be ensured during the transition period to avoid risking economic prosperity and growth of the world economy. (Elsevier Analytical Services, 2021) displays the connections of the energy sector research field to many interdisciplinary topic clusters and subfields, proving that the energy transition could not be solely focused on the technical aspect. Consequently, the approach of many researchers' factors in the implications of the transition at disciplines such as social, economic, or environmental.

Energy Policy

Under the evolving regulatory, financial, and technological framework of energy efficiency investments (EEI) and energy efficiency projects (EEP), significant upscale is required to meet the decarbonisation trajectory. As the maturity of the financial system regarding those type of investments and the maturity of the regulatory bodies legislating the emerging landscape is still inadequate, several risks and uncertainties accompany all energy related projects on different implementation phases. An attempt to classify risks following a systematic literature review has been performed by (Koutsandreas, et al., 2022). The risk category with the most references in literature is assigned to the regulatory uncertainties, in which the weak or volatile legislation and enforcement risk is dominant. The importance of comprehensive modelling of multiple parameters related to energy and climate modelling, enhancing transparency and accessibility of information on a structured and granular format is critical (Nikas, et al., 2020). In this scope, an integrated assessment modelling framework is being proposed to coordinate all efforts into one unified platform for energy and climate act modelling incorporating several future scenarios.

Following the uptake of new energy technologies, the increase of renewable energy investment and projects enhancing production, transportation, and end-use energy efficiency, underlines the need for developing the supportive mechanisms for monitoring and validation. Broad collaboration of the stakeholders involved in the energy sector is essential to materialise the energy transition effectively and transparently. Fulfilling the above market requirement, a study by (Flamos, et al., 2009) proposed a web-based scoring module, using Scientific Reference System (SRS). The parameters selected for the scoring algorithm fall into several main categories. The actual production performance and the installed capacity of the on-grid and off-grid facilities, the potential of each implementation based on the utilization status and the specific areas of improvement of each technology. Additionally, the socio-economic impact is assessed while the expenditures assigned to each technology for the research & technological development, implementation and operating costs are evaluated in comparison to the investment's lifetime, size, and energy efficiency. The methodology was applied in technologies, for which IEA has published reports such as biofuels production, power generation from biomass, nuclear power, hydrogen powered plants, fuel cells technology and carbon capture facilities providing a proof of concept for broader similar implementations.

Renewable Energy Production and Storage

Effective energy planning and sustainable energy production is a research field that attracts a lot of attention. At the broader sustainability scope, the selection of the energy mix affects many aspects of human activity. Consequently, assessment methodologies used in literature are related to the life cycle assessment of energy production and the impact of the alternative pathways to economic, social, and environmental activity. Several multi-criteria decision analyses (MCDA) methods and different weighting techniques have been evaluated by (Sahabuddin & Khan, 2021) to assess the sustainability of the energy production. The criteria selected cover three main pillars: the economic, social, and environmental aspects. The assessment was performed with seven different MCDA methods frequently used in the energy sector. The methods considered are Weighted Sum Method (WSM), Weighted Product Method (WPM), VIKOR, Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), Performance Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), Analytical Hierarchy Process (AHP), and Complex Proportional Assessment (COPRAS). The energy generation technologies selected for the scope of the subject study are a mix of fossil based and renewable alternatives. The fossil-based solutions selected were the broadly used coal, oil and gas fired plants along with nuclear energy production. For the renewable alternatives, hydro, solar, wind and biomass were assessed. For the weight assignment, experts' opinion was requested and considered. As the assessment methodologies differ, the ranking derived had significant variation, making the selection more complex. Additionally, a robustness analysis followed, to investigate the effect of weight variation on the concluding result of each method. Solar technology has been ranked the best under the Weighted Sum Method (WSM), Weighted Product Method (WPM) and Analytical Hierarchy Process (AHP). Nuclear energy production was the best under the TOPSIS and PROMETHEE framework, while biomass and wind were ranked first using VIKOR and COPRAS methods, respectively.

Similar evaluation of energy alternatives was performed by (Saraswat & Digalwar, 2021) for the case of India's energy sector, which was at the time of the study heavily dependent on the fossil fuels for energy production. Conventional and renewable energy sources for sustainable development have been evaluated based on an enriched criteria set consisting of economic, technical, social, environmental, political, and production flexibility aspects of the fuel technologies in question. The method selected is the integrated Shannon's entropy multi-criteria decision making, which uses Shannon's entropy method for applying weights and deploys fuzzy analytical hierarchy process (AHP) method for ranking. The energy production alternatives evaluated include thermal, gas, nuclear, solar, wind, biomass, and hydro energy options. The conclusion derived from the fuzzy AHP approach ranked solar as the best alternative. Further validation was performed by deploying different MCDM techniques without significantly changing the top rank solutions (ranking performed using PROMETHEE-II, fuzzy WSM, fuzzy WPM, and fuzzy WASPAS approach). According to the authors, current pledges of the government of India require considerable uptake and growth of renewable sources to be fulfilled. To achieve the targets set, obstacles need to be overcome as the natural fluctuation of the energy production from renewables create challenges in the instantaneous balancing between supply and demand, considering the difficulties in short term and long-term energy storage produced in renewable means. Therefore, to address these issues, energy mix scenarios have been developed and further evaluated. TOPSIS method has been used to rank the different energy scenarios concluding to an optimal energy mix scenario consisting of coal (49%), gas (4%), hydro (9%), small hydro (2%), nuclear (4%), solar (14%), wind (13%), biomass (2%), and imports (2%).

Following the pathway of renewable energy, raises an important issue for the design of energy storage systems. Balezentis et al (2021) deployed a multiple criteria technique to assess technological, economic, environmental, and social aspects of the most popular energy storage alternatives. The technologies evaluated are categorized into five groups: chemical storage, by synthesis of fuels using renewable electricity sources, electrical storage by supercapacitors and superconducting magnetic energy storage, electrochemical, such as batteries, electrochemical recuperators, mechanical storage using compressed air or liquid air form and thermal storage (The European Association for Storage of Energy, 2022). The interval coordinated TOPSIS method was used to incorporate the uncertainty factor of the interval domain of the criteria. The results of the analysis ranked hydro pumped storage (HPS) as the top technology. The second-best energy storage option depends on the methodology followed, The molten salt storage is ranked second under the distance measure, while according to the degree of coordination Compressed Air Energy Storage (CAES) is ranked at the second place.

Hydrogen Production Pathways

Hydrogen has been extensively discussed as a low environmental impact fuel with a great plus of the high energy density in terms of mass, however, requiring increased storage volumes due to its low density. At the study conducted by (Ruojue, et al., 2021) the cheaper but more carbon intensive production pathways of steam methane reforming and coal gasification have been evaluated along with the biomass gasification, dark fermentation, and electrolysis production pathways. Noting that the production process could significantly impact the environmental performance in terms of lifecycle emissions, the criteria selected cover environmental, economic, and social aspects of the technologies evaluated. The method used, was ELECTRE, to prioritize the alternatives under the context of hybrid information. The results were sensitive to the weights of criteria. However, the biomass gasification production process is evaluated as the best option by the authors. Hydrogen production is of significant importance as it is considered as the basic feedstock for a number of alternative future fuels, either carbon based synthetic hydrocarbons or enriched with nitrogen, resulting in ammonia, which are all considered as alternatives for hard to abate sectors, like maritime transportation. Those fuels could provide an alternative choice to the fuels produced from bioprocesses, which are under debate for their actual environmental performance and the questions arising from scaling up their production.

Alternative Marine Fuels

Within the scope of global energy transition, the maritime transportation sector has increased its focus on emission reduction technologies and efforts have been directed to the evaluation of fuel alternatives for the short-, mid- and long-term future. Providing a sustainable alternative solution though, requires sufficient advancement in several aspects, potentially competing, within the scope of the ESG principals. Balancing social and governance issues with the environmental performance and the economic sustainability of any application is a challenging task, which may depend considerably on the industry and specific details of the project at hand, along with the involved stakeholders' objectives and the country and legal framework applied (Psaraftis, 2019).

Research has been directed to the full life cycle of air emissions assessment. Under such framework the alternative pathways are being evaluated for their sustainable mid- and long-term efficacy (Gilbert, et al., 2018). The emission categories relevant to the use of marine fuels can be grouped into local pollutants, consisting of emissions with short lifespan in atmosphere, such as particulate matters, sulphur, and nitrogen oxides and greenhouse gas emissions such as carbon dioxide, methane, and nitrous oxides. For the purpose of the cited study, fuels that comply with the existing regulations for sulphur oxides emissions and alternatives that could potentially lead the sector's decarbonisation transition have been considered. The fuels selected are the conventional marine diesel oil and marine heavy fuel oil, along with liquified natural gas (LNG), hydrogen, methanol and bio-based diesel and LNG. Focus has been given to the process used for producing the alternative fuels, the region they have been produced, to assess the impact of transportation and feedstock properties, such as electricity and technology maturity and the unit used onboard for energy generation. The first two, correspond to the emissions before delivering the fuel onboard, while the engine type and combustion efficiency, affect the emissions at the stage of energy production onboard. The engines deployed in oceangoing vessels are mainly internal combustion units, either operating in Otto or Diesel thermal cycles. The conclusion of the research was that no existing alternative has the potential to drastically reduce the emissions, and the option of hydrogen can be a solution, considering the lifecycle CO2 emissions, only in the case of decarbonising the production process. This can be achieved either by applying carbon capture at the production facility if produced by fossil fuels or by using electrolysis for its generation. In parallel, the electricity used for both alternative production processes are required to be renewable, or similar, in terms of environmental footprint. The same applies for any synthetic fuel derived from hydrogen. For the bio-based fuels, considerable emissions reduction can be achieved, if the feedstock is capturing atmospheric CO2, that otherwise will not be captured. Biomass feedstock availability is an issue in scaling production. For the case of bio-LNG, which has considerable potential as a future fuel, an additional challenge is managing and eliminating upstream and operational methane emissions.

A broad analysis of the same scope, focusing mainly on future alternative marine fuels was performed by (Bilgili, 2021), assessing biogas, dimethyl ether, ethanol, liquefied natural gas, liquefied petroleum gas, methanol, ammonia, and biodiesel in the basis of the technical feasibility and operability, their environmental performance, the economic sustainability of the alternatives and other criteria and constrains considering the logistics and supply chain infrastructure, supply security, safety in operation, public opinion and ethics, political and strategical aspects. The conclusion remarks present biogas as the most environmentally friendly alternative. However, the analysis highlights that the production of biogas is mainly located in waste disposal facilities, detached from marine fuel supply chain, raising a challenge for the supply of biogas. Supply of biogas is additionally challenged by the difficulties and risks attributed to the storage and transportation of the fuel concluding that considerable developments are necessary before considering biogas as a feasible alternative for large scale deployment.

Similar research has been performed for a short sea application by (Spoof-Tuomi & Niemi, 2020) for a case where a vessel is engaged in specific trading route between Sweden and Finland. The subject vessel is equipped with a dual fuel, high rotating speed Otto cycle engine, capable of running on liquefied natural gas, liquified biogas and conventional marine diesel oil. The methodology used for the life cycle assessment of the alternatives was based on a 100-years global warming potential. The results showed that while liquified biogas has the higher well to tank CO_2 equivalent emissions, the total lifecycle emissions are considerably lower, less than half, from the second-best fossil-based alternative. Addressing the economic aspect of the alternatives, the authors concluded that while the transition is only possible by utilizing low-carbon and zero-carbon fuels, without carbon taxation or subsidies, the low carbon alternative of liquified biogas cannot compete sufficiently with the prices of fossil fuels. A study examining specifically the use of ammonia through computational fluid dynamics modelling (CFD) in compression ignition engines in marine application has been performed by (Rodríguez, et al., 2022). During the subject work different proportion of ammonia is injected through air intake, modelled through CFD. Thermodynamic efficiency, CO_2, CO, nitrogen oxides and hydrocarbon emissions were examined in the scope of the efficacy of ammonia solution for energy generation in onboard marine vessels.

Focusing on the gradual transition towards biofuels, (Bengtsson, et al., 2012) examined two pathways for the shipping industry, in a case study for a ro-pax ferry service. Lifecycle assessment (LCA) is used to evaluate the environmental performance of the diesel route, which describes the gradual swift from heavy fuel oil to marine gas oil as a temporary state and eventually to biodiesel. The second pathway assessed with the same framework is the gas route, which comprises of the shift from liquefied natural gas to liquified biogas. Blending biodiesel and biogas into MGO or HFO and LNG respectively is technically achievable and could contribute to gradually lowering life cycle carbon dioxide emissions and global warming potential. Comparing the two pathways, the authors concluded that gas route is environmentally preferable as the analysis shows a lower environmental impact for all categories and transition phases, except the initial primary energy use in 2020 and the global warming potential in 2025. A significant remark made is that during the gas pathway, focus should be given to methane leakages in the supply chain, as methane has higher global warming potential than carbon dioxide and could therefore have a large effect.

Understanding the need to reduce the greenhouse gas emissions, (Korberg, et al., 2021) have performed a detailed technoeconomic assessment of alternative marine fuels combining the fuel selection with propulsion technologies to be deployed in four use case scenarios of one large ferry, one general cargo vessel, one containership and one bulk carrier. The cost of the propulsion unit, the onboard fuel storage requirement, which is correlated with the vessel's autonomy and the reduction of cargo space due to the cumulative effect of all aspects applying, vary significant for each implementation, providing a multiparametric environment for the technoeconomic assessment and resulting combinational selection of alternative fuel and propulsion unit to be deployed in each case.

The alternative fuels and the production processes for each alternative have been effectively demonstrated as presented in Figure 2.

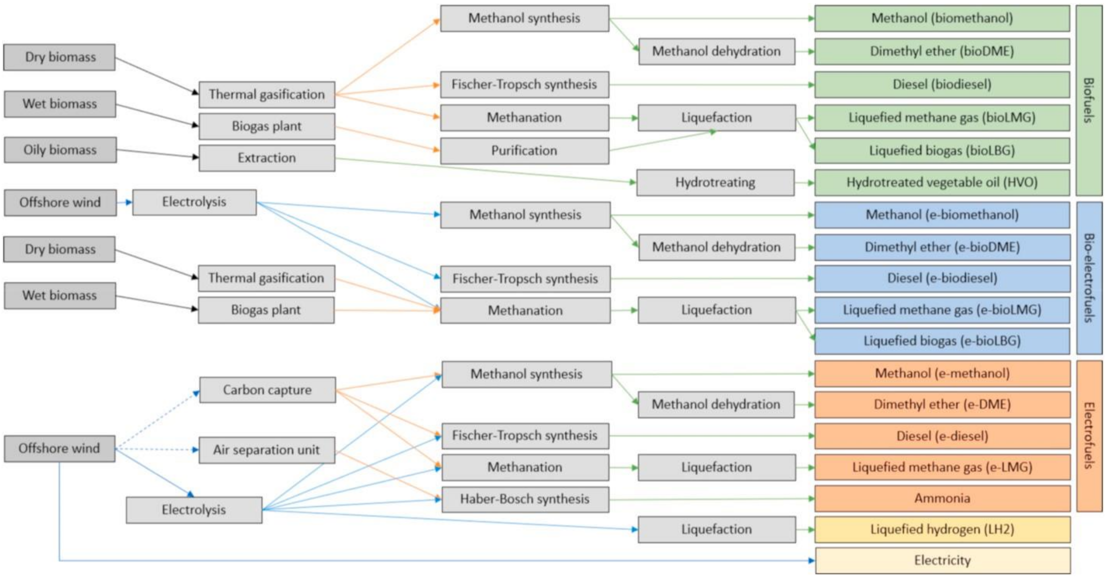

Figure 2. Overview of the fuel production pathways (Korberg, et al., 2021)

The methodology followed for the analysis provided has three main components. Firstly, the cost-based price of fuels to be delivered onboard, following different production pathways, including fuel handling, storage, transportation, and bunkering costs. The second component is related to the capital expenditure of the propulsion unit, including an approximation of the operating expenses and maintenance cost. Lastly, the third component, is the vessel related energy demand based on expected operational profile and required autonomy combined with the preceded fuel analysis to derive the Total Cost of Ownership (TCO) of each alternative. Uncertainties in fuel production costs and potential deviation from the base scenario have been explored through sensitivity analysis, as the cost may depend on external parameters, such as electricity of biomass feedstock price, production plant cost of investment, market balance etc. Similarly, the efficiency and capital expenditure of the propulsion unit is of high importance, thus it was also explored through a sensitivity analysis.

The results derived in the subject study, indicate that for vessels engaged in short standard route voyages, such as ferries, the battery electric solution is the alternative of choice. For the other three ship categories, methanol is the alternative that results in the lowest Total Cost of Ownership. Although, an explicit remark has been made, that the utilization rate and the production cost of fuel have a dominant role in the selection and variation of those parameters could significantly affect the conclusionary choice. An interesting observation in the study conducted is that with an improvement in efficiency of fuels cells in the range of 15-20% (Korberg, et al., 2021), they can provide a competitive alternative to the four stroke marine engines, while both propulsion unit technologies remain inferior choices to the two stroke marine engines utilized for the case of ocean-going vessels' application.

Emissions regulation has been rapidly developing the past years, both in global, regional, or local level. Along with the regulatory development, interest of the public and collaborators has been shifted to how companies are managing the transition, monitored through their sustainability reporting and corporate social responsibility initiatives. As several competing objectives, such as technical aspects, environmental performance, economical sustainability, social impact and scaling up potentials of each alternative need to be addressed and balanced in the most effective manner, an approach to assess multicriteria optimisation is being frequently selected.

To incorporate a selection of the above-mentioned parameters in the decision-making process (Deniz & Zincir, 2015) have performed a comparison of alternative fuels based on a broad criteria range. The study is examining the use of liquid fuels, as alternative to the currently used diesel and heavy fuel oil distillates. The alternatives assessed are methanol and ethanol, as one category, liquified natural gas and hydrogen. Methanol and ethanol are fuels that originate from fossil fuels; however, both are light alcohols that could potentially be produced from renewable sources either through a bioprocess using woody biomass, waste, or agriculture by-products or by synthesis of electro fuels. Liquified natural gas is selected in several marine applications, especially at the fast-growing segment of LNG carriers, with considerable reduction in the greenhouse gas emissions density, especially at 2-stroke engines for which the methane slip is limited. Methane, principal component of LNG, is a harmful greenhouse gas, with a global warming potential 28 times worse than carbon dioxide (GWP 100). Thus, limiting methane slip is of major importance in improving environmental performance of such applications. Lastly, hydrogen is a fuel with no big scale application, but very attractive and often found in literature due to the clean exhaust gases. Fuel storage stability, density and very high self-ignition temperature are some of the main disadvantages.

The comparison is done by assessing several criteria. Safety is of great importance in marine applications as the remote environment do not easily allow external assistance in case of emergency. Fuel characteristics imply risks to safety. Auto-ignition temperature, flammability limits and flame properties (e.g., hydrogen oxidises invisibly, no visible flame), are some of fuel properties relevant for the safety evaluation of alternatives. Global availability is of great importance for scaling the application to a significant number of marine vessels, with bunker capacity and energy density both in terms of weight and volume being critical to many ship segments. Other criteria assessed in the subject study, are the adaptability and the efficacy of a potential modification both on the existing global fleet and the vessels to be built. In all cases a detailed study is necessary, modifying the design and repurposing a lot of areas of the vessel leading to potential implications. Engine performance, efficiency of combustion, engine ware and maintenance costs along with the emissions of pollutants and compliance with the regulations are also included as criteria. In addition, selection of fuel is affecting the market placement as greener and more environmentally friendly solution are more compelling to major charterers and clients, but in contrary may also affect the cargo space and make the vessel unfit for specific trades. This, along with the capital expenditure and operating costs are important concerns that affect considerably the commercial aspect of any asset. For the ranking of the criteria, a survey has been performed (Deniz & Zincir, 2015), addressed to industry experts, resulting in safety being the criteria with the highest weight, following the Analytic Hierarchy Process (AHP) for calculating the weight of each criterion. Assessment of alternative fuels is done based on the comparison of the score on each criterion, weighted at their relative importance, however, no concrete conclusion has been achieved, with hydrogen being the most commercially effective alternative fuel according to this study.

Attempts to assess a broader range of alternative marine fuels, through a multi-criteria perspective, was carried out by (Hansson, et al., 2019) and (Xing, et al., 2021). Initially, focusing on the work done by (Hansson, et al., 2019), the seven alternative marine fuels assessed are fossil originated LNG, Liquified biogas (LBG) produced through anaerobic digestion and liquification process of organic waste (biomass), fossil methanol, produced through gas reforming of natural gas, renewable bio-methanol, originated from gasification of biomass into synthesis gas, fossil H2, produced through gas reforming, mainly methane reforming following desulfurization, H2 produced by electrolysis using renewable electrical energy from wind or solar power plants, and hydrogenated vegetable oil (HVO) originated for processed tall oil. Economic, technical, environmental, and social aspects are the main criteria in the assessment, which are further analysed in subcategories. Weighting of criteria and sub-criteria have been examined based on the combined preference of a group of shipping-related stakeholders, including governmental authorities, ship-owners' representatives, fuel producers and engine manufacturers. To test the robustness and evaluate uncertainties of the ranking, the authors performed a sensitivity analysis. The method applied for the evaluation of the alternative fuels is the pairwise comparison matrices approach, while the weights of each sub-criteria are defined through the analytic hierarchy process. The conclusion of this study shows that none of the selected marine fuel option is clearly superior against the others, as the priority of each stakeholder influence the result. Price driven views, of ship-owners, fuel producers and engine manufacturers align to the most cost-effective options, of fossil origin energy sources, while in contradiction governmental authorities, valuing most the environmental effect and greenhouse gas emissions derive to rank as preferred choice the renewable alternatives, such as renewable hydrogen, renewable methanol, and biofuels. Aligning the governmental objectives with the market to support the penetration of renewable energy sources in maritime transport requires policy initiatives related to environmental performance and subsidies for renewable alternatives. At the study performed by (Xing, et al., 2021), the ranking is conducted based on qualitative criteria for a broad assessment of 11 alternative pairs of fuels and energy production units (examining Internal Combustion Engines and Fuel Cells technology). Renewable methanol is the energy source with the highest ranking for global applications, while the internal combustion engine is the preferred energy production unit of choice. A comprehensive graph created by the authors of the subject study, providing the ranking and the applicability of the alternatives is shown below.

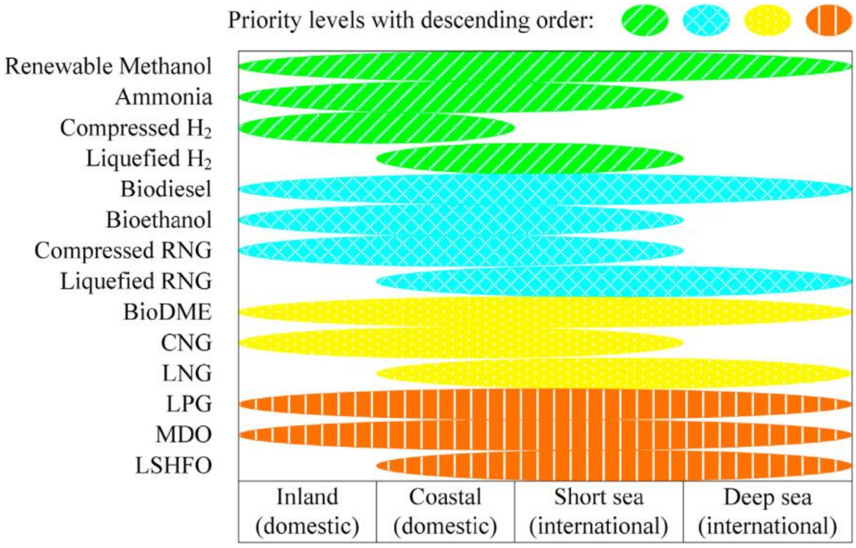

Figure 3: Priority levels and potential applications of different marine fuels (Xing, et al., 2021)

Focusing on multi-criteria decision-making methods, under uncertainty and incomplete information, (Ren & Lutzen, 2017) have examined the alternative energy pathways to mitigate the energy transition and the environmental performance of the maritime industry. The criteria to assess sustainability are classified in four main categories, namely, the technological, the environmental, the economic and the social-political attributes. Under the category of technological attribute, the volume of applications and experience in handling each energy source is defined as the subcategory of technological maturity, the robustness and dependence on externalities is reviewed under the reliability aspect, while the energy storage efficiency subcategory is defined as the fuel power density and the required refuelling frequency. On the economic aspect, the availability, or the need for further development of supporting infrastructure is assessed, along with the capital expenditure required for shifting to the alternative technology and the operating expenses, including bunker prices, expected repair and maintenance costs, and collateral training and crew wages costs. On the environmental criteria, greenhouse gas emissions, namely, carbon dioxide, methane, nitrous oxide, hydrofluorocarbons and perfluoro octane sulphonate are assessed on their global warming potential, while local pollutants, such as sulphur oxides, nitrogen oxides and particulate matters are also considered for their local environmental effect. Lastly, the social-political aspect consists of three sub criteria, the social acceptance, thus the view of the public regarding the alternative energy source, the governmental support, which is the group of measures and regulations affecting the competitiveness of each alternative and the safety of ship operation under the new conditions derived from the selected energy source. For addressing non scalar inputs, linguistic terms, incomplete information, and uncertainty in the parameters reviewed, the Dempster-Shafer technique has been used to support the use of Analytic Hierarchy Process for determining criteria weights. A variation of AHP was employed in the subject study in a fuzzy logic approach that fits better with the characteristics of the dataset provided. The case study was focused on three alternative energy sources. The first alternative is liquefied natural gas (LNG) burned in dual fuel engine delivering ship’s propulsion power. Secondly, nuclear power generation through controlled chain reactions in addition to a coolant for transforming heat into useable power has been assessed. Lastly an alternative depending on renewable wind, utilizing flettner rotors, kites, spinnakers, sails, or wind turbines is normally used as a supplementary power generation and could provide future energy source. Initially, the weighting process, both for the conventional

AHP and fuzzy approach, showed that the aspect of the highest importance in the technological criteria, with technological maturity being the predominant consideration. It is useful to note that differences regarding the weights derived from analytic hierarchy process and trapezoidal fuzzy analytic hierarchy process are limited. The sequential ranking reveals relative superiority of the nuclear alternative against the other two options. A similar approach has been followed by the authors (Ren & Lutzen, 2015) on their published study on multicriteria decision making method for evaluating the sustainability assessment of alternative marine fuels for sulphur oxides reduction from shipping, combining Fuzzy Analytic Hierarchy Process (FAHP) and VIKOR. Fuzzy AHP was used to determine the weights and the relative ranking of alternatives on the criteria set, and VIKOR was used to provide the priority ranking of alternative energy sources. Transitioning away from HFO has been a research item explored by (Ren & Liang, 2017) through a holistic sustainability perspective. A multicriteria decision making approach was followed, using fuzzy logarithmic least square method for establishing weights of the sustainability criteria, while a fuzzy TOPSIS has been employed for ranking the alternatives based on the criteria set selected. The alternatives explored are transitional future marine fuels, including methanol, LNG and hydrogen. All of them providing better environmental performance on tank to wake basis compared to the common and widespread solution of HFO. The criteria selected are arranged in four sustainability criteria categories, namely, the environmental, the economic, the technological, and the social aspects. The environmental criteria category consists of four indicators, including the effect on CO2 emission reduction, effect on NOx emission reduction, effect on SOx emission reduction, and effect on PM emission reduction. The economic aspect incorporates two criteria, namely, the capital expenditure and operational cost. The three criteria composing the technological dimension are the maturity, the reliability, and the capacity of each alternative. Lastly, social dimension includes two criteria, which are the compliance status with emission regulations and social acceptance. Fuzzy theory allows the use of linguistic variables in the criteria set transforming them into fuzzy numbers which are compatible with comparison matrices. According to the framework followed, hydrogen is ranked as the best alternative, providing the best environmental performance, high renewability potential, if produced through electrolysis utilizing renewable electricity or other low carbon power sources, compliance with the emission regulatory requirements and high social acceptance score. However, it is useful to note that while the tank to wake environmental performance of hydrogen fuels is superior to other alternatives, well to wake emissions depend heavily on the production process. Currently the majority is produced through processing of fossil fuel and grid electricity resulting in significantly worse lifecycle environmental score.

Alternative Fuel Pathways

As maritime industry explores its future alternative energy sources, many options have been proposed matching different trading requirements and diversifying the shipping primary energy source landscape (Maritime Knowledge Centre, 2020), demonstrating a possible shift towards a multifuel future.

For the current study, multiple low carbon alternatives have been identified and assessed, focusing on long term options for dense energy consumers (ocean going vessels). The fuels selected are biodiesel, bio-methane (LBG) and bio-methanol, e-hydrogen, e-ammonia e-methane and e-methanol. The feasibility assessment of the selected alternatives is being evaluated under the framework of marine applications. The mosaic of life cycle assessment methodologies and standards used in literature, among which are the GREET model, RED II (employed at FuelEU Maritime Regulation proposal), U.K. DEFRA and others; create a difficult to navigate ecosystem. For the same fuel and production pathway, these models can produce different assessments, varying significantly on life-cycle emissions. The reasons for this are known and include different assumptions in the models, different boundaries for life-cycle analysis, attributional versus consequential life-cycle analysis, etc. In that sense, the industry would benefit from the creation of a commonly accepted international standard. Currently, the IMO is looking at introducing a global framework on life cycle GHG and carbon intensity guidelines for marine fuels, which could impact other IMO regulations and regulatory development on regional level, e.g., European Union.

Bioethanol and biodiesel are commercially produced globally, though they have almost exclusively been utilized by the road transportation sector. The established shipping operational procedures make customizing marine engines to run on new compatible fuels a costly process. Thus, it is practical to take advantage of the existing infrastructure (marine engines, fuel transport pipelines, bunkering) and produce a fuel compatible with what is already in place. Such drop-in fuels fit existing infrastructure and do not require a high investment in ship engine or infrastructure changes. The advantage of producing a marine fuel is that the fuel can be of a lower quality, has higher viscosity, and is less refined than fuels used for aviation or road transport. Thus, marine biofuels may be produced with lower processing costs, eliminating the need for secondary refining.

Biofuels Pathway

The combined effects of decreasing availability of light crude oil, stricter financing on conventional oil & gas investments, the volatility on prices and concerns regarding energy security followed by the projected increase of demand for global merchant shipping, and stricter marine fuel regulations have caused a search for competitive alternative marine fuels. Alternative fossil-based fuels such as LNG and LPG have low sulphur and nitrogen oxide emissions but have a limited contribution to reducing greenhouse gas emissions, while falling in the fossil-origin fuel category. Biofuels, however, have a much larger potential to combat climate change and reduce emissions over their full life cycle. Even though biofuels are not yet widely used in the maritime sector, it is possible that based on existing biofuel technologies, marine biofuels can be designed and produced to be technically compatible with marine engines. The fuel flexibility and the wide range of fuel attributes marine diesel engines could operate on, creates the context and the conditions for the development of new biofuel processes combining different grades and types of biofuels. As biomass is a renewable resource and contains very little or no sulphur, biofuels have the potential to become an important part of the fuel mix in the shipping sector, either as drop-in or alternative energy source, thereby limiting the dependence on fossil fuels while providing a reduction on the GHG emissions of the sector.

Biodiesel Pathway

Biodiesel can be produced from various biomass feedstocks. Selection of feedstock has significant consequences since it is the element that affects the total cost of biodiesel, the most, and mandates the lifecycle greenhouse gas emissions (van der Maas, 2020). First-generation edible oils such as soybean, rapeseed, and palm oil could be the primary energy source for biodiesel but are avoided in a lifecycle perspective, due to their competition with the food industry resulting in occasion to higher lifecycle emissions than conventional fossil fuels. Therefore, second-generation non-edible vegetable oils, waste oil and animal fats are more suitable as the primary energy source to produce biodiesel. Second-generation feedstocks mitigate land-use change issues and offer lower lifecycle GHG emissions than first-generation feedstocks. Currently, hydrotreated vegetable oil (HVO), Soybean Methyl Ester (SME) and fatty acid methyl ester (FAME) diesel are the most promising alternatives, making their debut on biofuel trials, entering progressively the shipping fuel markets.

Bio LNG, Bio-Methane (LBG) Pathway

The main component of liquefied natural gas (LNG) is methane (CH4), the hydrocarbon fuel with the lowest carbon content and therefore with the highest potential to reduce CO2 emissions, resulting in the rapid uptake of LNG as a marine fuel to align with the short-term targets. The supply chain of LNG, bunkering facilities, and engines capable of running on LNG have been developed and market scalability has been carefully assessed. This provided an advantage to bio-LNG alternative, as the same infrastructure can be used and the potential gradual blending with conventional LNG at different ratios can provide a cost-effective way to progressively migrate into high bio blends when prices start to converge. Primary energy sources for bio-LNG could be agricultural and municipal waste streams and second-generation lignocelluloses biomass. Manure from livestock is an agricultural waste stream that could be exploited for the production of bio-LNG, as a burden to meat and poultry industry affecting significantly the sector’s emissions. Alternatively, agricultural waste streams that can be utilized comprise of crop residues from the harvest or harvested crops that are grown for purposes of avoidance of erosion or preservation of fertility of the soil. Organic fractions of municipal waste or wastewater sludge could also be a potential feedstock source. The above-mentioned waste streams do not affect the food supply; thus, they have great long-term potential. The conversion from feedstock to bio-LNG involves anaerobic digestion or gasification. The agricultural and municipal waste streams are put into anaerobic digesters, where microorganisms break down the organic matter in the absence of oxygen forming a mixture consisting of pure methane, carbon dioxide and other gases. Methane is isolated and separated through water scrubbing and membrane separation, followed by a liquefaction process. Lignocelluloses or woody biomass is marketed as another feedstock option for bio-LNG requiring a different conversion route consisting of gasification of lignocelluloses to produce bio-LNG. Woody biomass is broken down in a high-temperature reactor under high pressure. Syngas is formed, mainly consisting of hydrogen and carbon monoxide, which is then cleaned from contaminations and forwarded into a methanation process to form methane. The resulting methane is also liquefied to obtain bio-LNG.

Bio-Methanol Pathway

Methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel that can be stored in liquid form at ambient temperature at atmospheric pressure, making storage less expensive compared to LNG and hydrogen. The low average energy density and heating value of 19.5 MJ/kg, (American Bureau of Shipping, 2022) increase the required tank volume to approximately 2.5 the size of the tanks of conventional heavy fuel oil widely used today. Bunkering facilities and supply are in place at a limited scale, providing a tested path for further deployment.

Guidelines for bunkering are available and standards and safety concerns on operation do not represent a major challenge. Bio methanol can be produced from several different feedstock resources, including black liquor from pulp and paper mills and sustainable lignocellulosic biomass feedstocks. Alternative lignocellulosic biomass sources can be a mix of wood, willow or forest residues, forest thinning or agricultural waste, which are second-generation feedstocks. Production process of bio methanol is based on syngas formation produced in through gasification of biomass. Syngas is then pressurised into a reactor through insertion of a catalyst to form methanol. Methanol is liquid at ambient temperature and pressure, making it a favourable marine fuel in terms of storage and handling, while conventional diesel engines require minimal adjustments to be compatible with methanol as primary energy source.

e-Hydrogen and Electro Fuels Pathway

e- Hydrogen is produced using electricity as the primary energy source. Under the regulatory frameworks propounded, which are considering the lifecycle assessment of marine fuels, the futureproof option is to produce hydrogen based on renewable energy or “GHG/ carbon free” grid power under the process of electrolysis. Electrolysis can be conducted at plants of three alternative electrolysers technology, with different maturity each. Alkaline water electrolysis is the technology broadly used today, while solid oxide electrolysers have demonstrated improvement in the production efficiency and currently are considered on new plant development, while still the capital expenditure per installed capacity is higher than alkaline plants. Polymer electrolyte membrane (PEM) electrolysis is an alternative that has a market share, mainly due to older installation, as the efficiency of the system is low, and the capital required is high compared to the other options. Developments related to hydrogen's transportation, production, safety, standards, and regulation are being assessed thoroughly before incorporating hydrogen into shipping fuel supply chain (American Bureau of Shipping, 2022). The role of hydrogen on the emerging energy transition at hard to abate sectors, such as ocean-going maritime transport, is expected to be of significant effect. Finding volume-efficient ways to store hydrogen is a challenge. Commonly, it is stored either as compressed gaseous hydrogen (CGH) or cryogenic liquid hydrogen (LH2). Liquefaction through compression requires considerable amount of energy, significantly reducing the total energy efficiency of the process and increasing the cost of liquid hydrogen considerably. Additional concern is that hydrogen molecules are small and can diffuse through many materials including metals. This is mainly an issue for compressed hydrogen (typically stored at 250-700 bar) where the molecules are penetrating storage material (DNV GL , 2019). Thus, there are two main safety concerns with hydrogen related to storage; metal embrittlement (and eventually fracture) and gas leakage. In summary, the use of hydrogen as a marine fuel introduces some concerns regarding its future use, mainly due to high production, storage, transportation costs and safety issues that are difficult to be overcome in the remote environment of an offshore vessel, creating doubts regarding the widespread exploitation of this alternative.

Nevertheless, the importance of green hydrogen for the decarbonisation and the energy transition of the maritime industry is not devalued. Green hydrogen is the primary building block for all synthetic fuels, that are projected to increase their uptake as the industry progresses at its decarbonisation journey. Electro fuels, either carbon based or nitrogen-based (ammonia) provide a solution to the above-mentioned issues of hydrogen, delivering a more stable, operational and easier alternative. Understanding that each of the synthetic fuel options have its own implications, exploration of the constrains of each selection need to be carefully evaluated. Carbon-based electro fuels can be produced from non-biogenic CO2 and in combination with biogenic CO2 sources to co-produce bio-electro fuels, by increasing the yield of biofuel production. Purely synthetic hydrocarbons can also be explored. Carbon dioxide can be obtained from different sources. It can be captured through a capture and utilisation (CCU) system from fossil -fired plants and industrial sources (point-source capture), such as coal-fired power plants or steel manufacturers. This carbon source can provide the required volume of CO_2 at a competitive price range, creating opportunities on the short term, but it does not provide a sustainable long-term solution, as it still emits CO2 from fossil fuels. Another option would be CO2 capture from biomass combustion or processing, as the carbon is originated from plant base carbon initially pulled out from the atmosphere. A third option is capturing the carbon dioxide directly from the air (direct air capture), which is expensive and is projected to remain on high price range as the system capital cost is significant and the efficiency of the system is low, as the carbon density of the air is thin.

e-Methane Pathway

Similarly with the LNG and LBG, use of e-methane can be boosted by the maturity of LNG supply chain, bunkering facilities, and engines advancements allowing the use of such fuels in a great range of applications. The main feedstocks for producing e-methane are low emission electricity which is utilised to produce hydrogen, water, and a carbon source carrier to synthesise the carbon-based alternative fuel. For the electricity required mature technologies like solar, wind and hydro exist, but not at the scale required. Significant investment is directed to renewable energy production, however the capacity of the energy produced to be assigned in hydrogen production, either on a business model of dedicated facilities and renewable farms/plants or based on storage of reserve electricity production business model is yet to be seen. Key challenges in the production of e-methane therefore remain availability of power-to-X (P2X) technology and scaling of low emission electricity, availability and competitiveness of electrolysers and production of e-Hydrogen (Maersk Mc-Kinney Moller Center for zero carbon shipping, 2021). An additional concern is identifying the sustainable source of CO2 which will be essential for the potential upscaling of e-methane production. The size of e-methane plants is likely to be limited by the scale of CO2 source supply, thereby the effect of economies of scale may diminish, keeping the cost of e-methane high, thus limiting the expansion potential of such alternative.

e-Methanol Pathways

Many processes for production of e-methanol are similar to the production of e-methane. Methanol can be formed out of CO_2 and hydrogen in a hydrogenation reaction which is catalysed by copper- or lead-based compounds. An alternative pathway for production of e-methanol can be through syngas; carbon dioxide is transformed into carbon monoxide and mixed with hydrogen to form syngas, then methanol is synthesised in a reactor where the syngas is pressurised and catalysed. Availability of renewable energy sources for electricity and hydrogen production is a key parameter, while as in the case of all carbon-based power-to-X (P2X) technology, availability of renewable and sustainable CO_2 source is expected to be a constraint. As explained in detail, methanol is a fuel with minimal complications in safety and operations, but the low energy density, increase significant the volume of tanks required to meet the expectations of the sailing range autonomy. Engines are commercially available, and operational experience has been obtained in the past decade for onboard different ship types. Onboard NO_x emission reduction is required for regulatory compliance, which can be achieved by using known technologies. Methanol combustion does release CO_2 tank-to-wake, as it is a carbon-based fuel, however, for e-methanol produced with carbon sourced from a biogenic source, close to net zero emission can be obtained well–to–wake, hence it is considered a viable low emission marine solution.

Ammonia Pathway

Ammonia synthesis using natural gas as feedstock is a mature technology but cannot lead in the decarbonizing shipping as it emits more greenhouse gas pollutants when considering the total lifecycle emissions, on a well-to-wake basis. The use of renewable electricity as feedstock for producing the needed hydrogen drives the cost, as the commercially mature electrolysers are currently too expensive and inefficient to make e-ammonia a competitor to other alternative fuels and fossil fuels. Global electrolyser production capacity is not ready for massive power-to-X roll-out in large scale. With an energy transition to renewables, ammonia will have the potential to become a carbon free energy carrier with higher volumetric density than hydrogen, solving a fundamental problem of carrying hydrogen. However, the current maturity is low and green ammonia is expensive, bunkering infrastructure is non-existing and not compatible with existing systems, limiting the feasibility for use as an alternative fuel. Considering the toxicity of ammonia, the potential risk of exposure of crew from leakages is a major concern, while on the technical aspects the development of tank storage solutions and expected strict standards for bunkering and safe operation for larger ammonia volumes may present a challenge. On the regulatory domain, some classification societies have released early guidelines for ammonia-fuelled vessels, which present inconsistencies as the approach is unified. Fuel cell technologies and dual or triple-fuel engines capable of burning ammonia with the use of diesel as pilot burner, are being designed and soon will follow pilot testing phase. Possible after treatment of exhaust requirements are currently unknown but are expected to be addressed through currently available technologies. Combustion of ammonia does not produce CO_2 emissions as no carbon is contained in the fuel – except from the quantity of needed pilot fuel if it is carbon-based. Solid Oxide Fuel Cells (SOFC) may run on ammonia directly, but SOFCs are significantly less mature and cannot be considered an option at the moment.

Review of the Selected Criteria

Alternative marine fuels differ in many aspects regarding their technical, environmental, economic, and social attributes (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022). Technical characteristics, such as energy density, technological maturity, environmental performance, cost aspects, feedstock security, scalability and availability of feedstock, transportation, storage, and infrastructure requirements vary for different fuels, which means that several elements of value and supply chain of each alternative fuels would influence their potential feasibility and scalability for maritime applications. Considering the barriers of application environment and the uncertainties induced by the premature stage of development, flexibility on pivoting to similar solution pathways is an advantage while assessing the feasibility of an alternative. Safety of operation has always been a major concern and could eliminate or limit considerably alternatives that are difficult to handle, that for example may have low flash point increasing the flammability and explosion risk or expose seafarer to environments of high toxicity, either as fuel or by its exhaust. Thus, a structured representation of the criteria categories and the areas of concern is to follow. The criteria following a linguistic/qualitative scale are evaluated under the following scale:

Linguistic term	**Scale**
Negligible	0
Low	1
Medium	2
High	3
Perfect	4

Table 3: Linguistic/qualitative scale

Technical Aspects

For the technical aspect, the criteria selected consider four inputs. The first two are related to a constrain resulted from the limited space available onboard. The energy density of the fuel is of high importance. The volumetric density is being considered, as the space required to store bunkers is negatively correlated with the availability of cargo space. This may be partly countered by the utilization of deck space on the vessels' segments that this solution can be explored and at the cases where safety of the crew is not jeopardised. Energy density per mass is also important as the total weight that can be carried safely is predefined for each vessel design according to international rules, thus increase in the energy density per mass is negatively affecting the maximum loading capacity. Some fuels are well matched with existing power generation systems, while other alternatives do not fit well into the existing propulsion technologies choice palette. Yet there is no obvious choice of power generation system that could dominate in the future, as new developments on the marine propulsion energy plant are already announced by the major suppliers/ manufacturers of marine engines and equipment. The feasibility of the power generation system and fuel option combination are discussed thoroughly in the industry and could provide a market enabler for the solutions firstly available.

Technical Criteria		Bio Diesel	Bio LNG/ LBG	Bio methanol	e-Hydrogen (lq) -ICE	e-methanol	e-methane/ e-LNG	NH3
Energy density [4]	Volumetric (MJ/m^3)	34	22.4	15.9	8.5	15.8	22.4	12.7
Energy density [5]	Per mass (MJ/kg)	44	50	20.1	120	19.9	50	18.6
Technological[6]	Maturity (Propulsion)	3	3	2	1	2	3	1
Technological[7]	Energy Efficiency	24%	22%	24%	31%	25%	22%	23%

Table 4: Consequences of technical criteria

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[4] (Hsieh & Felby, 2017), (Directive (EU) 2018/2001, 2018)

[5] (MEPC.308(73), 2018), (Hsieh & Felby, 2017), (Directive (EU) 2018/2001, 2018), (van der Maas, 2020)

[6] (van der Maas, 2020), (MAN Energy Solutions, 2021) (MAN Energy Solutions, 2020)

[7] (Korberg, et al., 2021), (van der Maas, 2020)

Environmental Aspects

Environmental performance is the key driver of the energy transition currently underway in shipping. As a result, low climate impact, meaning low greenhouse gas emissions, usually measured on grams of carbon dioxide equivalent is the decisive factor. The most important feature of the developing regulations is the underlining framework, which is expected to be the lifecycle emissions of each alternative. Compliance with the existing and future regulations is the key incentive for shipowners and shareholders. The well-to-wake (LCA) GHG emissions includes emissions from production, transport, and storage of each fuel, as well as conversion to mechanical energy in the form of torque on the shaft and eventually propulsion power of the vessel. The resulting comparative measure of well-to-wake emissions is the mass of CO2 equivalent emissions per unit of output energy. This implies that the well-to-wake emissions within each of the 7 energy carriers/ alternatives and converter pathways in this study will vary, depending on how and where the fuels are produced, mode of transport and storage, and onboard system efficiency. Another environmental aspect, which has already been regulated is the local emissions, consisting of sulphur oxides, nitrous oxides emissions and particulate matters. Local emissions depend on the fuel used and the engine or converter selected. NO_x emissions contribute to the formation of ground-level ozone, which has harmful effect on human health, while also form of acid rain and therefore cause damages on city structures and reduce the quality and fertility of soil. Similarly, SO_2 is known to cause acid rain and affect human health as well. SO_2 lifespan is short and as an endothermic reaction has cooling effect, while when drain it increases soil acidification resulting in lower productivity and fertility. Particulate matters at high concentration are known to be correlated with many diseases, including higher chance of cancer.

The scores of local pollutants are linearly converted to scale to be aggregated. The formula expressing the standardised score is given below:

$$\text{Standardised score}(x_{ij}) = \frac{(\text{Score } (x_{ij}) - \text{Lowest score}(x_{in}))}{(\text{Highest score}(x_{in}) - \text{Lowest score } (x_{in}))} * 100\%$$

Equation 1

A combined standardised score for local pollution is obtained by weighting the different local pollutants according to the WHO Guidelines for Air Quality (Gurjar, et al., 2007); as following:

$$\begin{aligned}&\text{Other local pollutants}\\&\quad = \frac{2}{7} * \text{Standardized score (SOx)} + \frac{1}{7} * \text{Standardized score (NOx)}\\&\quad + \frac{4}{7} * \text{Standardized score (PM)}\end{aligned}$$

Equation 2

Environmental criteria		Bio Diesel	Bio LNG/ LBG	Bio methanol	e-Hydrogen (lq) -ICE	E-methanol	e-methane /e-LNG	NH3
GHG Emissions[8]	WtW CO2e (grCO2e/KWh)	50.08	16.2	15.06	3.6	33.3	28.5	4.54

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[8] (Directive (EU) 2018/2001, 2018), (MEPC.308(73), 2018) (European Commission, 2021), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)

Other local pollutants [9]		1.00	0.22	0.08	0	0.08	0.22	0.05
	Sox (gSOx/kWh)	0.4	0.18	0.02	0	0.02	0.18	0
	Nox (gNOx/kWh)	12	2	3	0	3	2	3.8
	PM (gPM/kWh)	0.44	0.05	0.02	0	0.02	0.05	0

Table 5: Consequences of environmental criteria

Economical Aspects

Marine fuels that use the current infrastructure are preferred, as they avoid costs related to the disruption of current infrastructure and significant investments for new infrastructure. A fuel infrastructure includes fuel transportation systems, storage tanks, and bunker facilities, both in the port and supplier side as well as on board. Marine fuels that have comparable characteristics with the widely used HFO and MGO are desired, even similar properties as LNG and methanol are preferred, as the technical expertise and project feasibility are available at some scale. The capital expenditures of the propulsion system on board of a vessel are essential to shipping companies. High capital expenditures are barriers to entry for the adoption of new technologies, even if the pay-back period is acceptable. The propulsion system cost is estimated and measured in US dollar per installed capacity (kW). These prices are indicative, approximated by the most recent published studies, however, as the development of such technologies is on an early stage with an accelerated pace and optimization of the production is evolving, prices could differ in the future, making such alternatives more competitive. Additionally, scaling applications which now is phasing technical obstacles will provide lower capital requirements than the linear model used at this study. Capital expenditure include cost components such as the cost of the engine, or convert, fuel system, storage tanks, additional insulation or safety mitigation retrofits required. Another cost aspect very sensitive for shipping operators, is the cost estimate of fuel per energy potential content. As the value chain is not mature for the considered alternatives, fuel cost estimates, while essential, they are projected based on approximated production cost and potential supply and demand balance, which is extremely volatile and could be even affected by future regulation or subsidisation policies, let alone variables such as the cost of materials, feedstock prices and corporate environment.

Economic criteria		Bio Diesel	Bio LNG/ LBG	Bio methanol	e-Hydrogen (lq) -ICE	E-methanol	e-methane /e-LNG	NH3
Capital per installed KW[10]	CAPEX ($/kW)	600	870	617	1810	617	870	920
Fuel Cost[11]	Fuel cost ($/GJ)	26.4	25.3	19.2	42.5	33.1	31.9	33.3

Table 6: Consequences of economic criteria

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[9] (Directive (EU) 2018/2001, 2018), (Bengtsson, et al., 2012), (Gurjar, et al., 2007), (Bengtsson, et al., 2012), (Gilbert, et al., 2018), (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)

[10] (van der Maas, 2020), (Maersk Mc-Kinney Moller Center for zero carbon shipping, 2021), (Gilbert, et al., 2018),

[11] (van der Maas, 2020), (Maersk Mc-Kinney Moller Center for zero carbon shipping, 2021), (Korberg, et al., 2021)

Scalability Aspects

Different alternative fuels/pathways have different potentials for maturing and scaling-up, depending on factors such as technical restriction on the output capacity, cost and availability of materials and feedstock, which may drive prices into uncompetitive ranges, environmental performance, and applicability. Additional parameters affecting the potential adaption is the current usage of similar technologies, cross-sectoral demand driving innovation and investment, global availability, projected and actual future investment on the technology, global production potential; are all important for scalability, closely linked to supply chain development and infrastructure. Criteria have been adjusted into a scalar range of 0-4 based on the qualitative assessment described in Table 3.

Scalability criteria		Bio Diesel	Bio LNG	Bio methanol	e-Hydrogen(lq) -ICE	E-methanol	e-methane /e-LNG	NH3
Scalability[12]	Qualitative scale	4	4	3	2	3	4	2

Table 7: Consequences of scalability criteria

Safety of Operation Aspects

There are many aspects relating to the safe implementation of alternative fuels projects onboard ships. Attention is to be paid to fuel characteristics of applications powered by unconventional fuel sources such as low-flashpoint fuels. The flash point of a chemical substance is the lowest temperature at which a liquid can form an ignitable mixture in air near the surface of the liquid. The flash point is an indication of how easy a chemical may burn. Materials with higher flash points are less flammable or hazardous than chemicals with lower flash points. A lower flash point is an indication of fuel that can be ignited at lower temperatures, and in the absence of additional safety measures, this indicates higher risk on operation. Major safety issues are associated with fire, explosion, and toxic hazards due to the nature of the low-flashpoint fuels. Crew onboard ships are required to be trained on the awareness of the hazard, appropriate handling of such fuel, as well as mitigation and safety measures to be taken and qualified in accordance with recognized standard. The design and installation of systems and applications powered by alternative fuel are to follow an applicable statutory and class requirements framework which is being developed by industry's regulatory bodies. The associated levels of risk define the safety considerations related to the transportation and bunkering of the marine fuel followed by the onboard handling of the fuel by the vessel. The higher the safety risks, the higher the required safety measures creating a challenge in mitigation, resulting in reducing the competitiveness of actual applications. The criteria have been adjusted to a scalar range for the purpose of simplification of comparison.

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[12] (Korberg, et al., 2021), (DNV GL , 2019), (Maersk Mc-Kinney Moller Center for zero carbon shipping, 2021), (van der Maas, 2020)

Safety criteria		Bio Diesel	Bio LNG	Bio methanol	e-Hydrogen(lq) - ICE	e-methanol	e-methane /e-LNG	NH3
Flammability risk[13]	Qualitative scale	0	0	2	4	2	0	1
Toxicity[14]	Qualitative scale	0	0	2	0	2	0	4

Table 8: Consequences of safety criteria

Social Acceptance Aspects

Social acceptance is the first social-political criterion that could summarize the positive or negative public attitude towards technologies and fuel alternatives. The social acceptability of energy technologies is based on the public knowledge, community perception, and fear on potential implications (Assefa & Frostell, 2006). This is of high relevance for the assessment of alternative energy sources, as the public acceptability could drive or put back the development of alternative pathways, redirect research and development funds on innovative propulsion systems and affect financing opportunities. The criterium is measured on an ordinal scale which is presented below.

Social acceptance criteria		Bio Diesel	Bio LNG	Bio methanol	e-Hydrogen(lq) - ICE	e-methanol	e-methane /e-LNG	NH3
Social acceptance[15]	Qualitative scale	2	2	2	1	3	3	0

Table 9: Consequences of social acceptance criteria

Methodology

Multiple criteria decision making (MCDM) methods provide an effective way to navigate decision makers to evaluate and select the best alternative given multiple parameters and criteria categories. The VIKOR method is balancing the trade-off between the maximum group utility of the majority (aggregation of all criteria) and the minimum individual regret of the opponent (each of criteria).

The additional complexity of the implementation of a MCDM method on alternative fuels for maritime sector is that according to literature the weights of the criteria differ significantly. Depending on the scope of the research, the view of the interviewees and the stakeholders involved in the study, the weighting of criteria is inconsistent. This could be explained as the interests of the involved stakeholders focus on different aspects of operation and on different parts of the value chain. (Deniz & Zincir, 2015) focus on safety of operation and regulatory compliance. The regulatory aspect differs slightly from the view of the current study, as at the time the subject work was published the focus was concentrated on initiatives to achieve compliance for local pollutants reduction, which was an important subject and regulatory development the past years. The experts questioned for ranking of the criteria, have working experience onboard ships as engineers. This provides a certain point of view as the safety of operation is the first and most important aspect of work as crew. At the recent study of (Xing, et al., 2021) the gap in convergence of driver incentive of all involved stakeholders is raised. The authors split the interested parties into a governmental authority leading group, focusing on social and environmental criteria and a market

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[13] (DNV GL , 2019)
[14] (DNV GL , 2019)
[15] (DNV GL , 2019), (Assefa & Frostell, 2006), (van der Maas, 2020)

driven group, consisting of operators, shipowners, management companies and manufacturers weighting more the economic and technical feasibility. The ranking of the criteria in descending priority are ranked in the order of environmental impact, supply availability and reliability of feedstock source, technical viability, and lastly economic factors. According to the work performed by (Hansson, et al., 2019), Swedish stakeholders related to shipping, including representatives of ship-owners, fuel producers, engine manufacturers, representatives of government authorities, and researchers, have identified the most important criteria for decision making. The top two most weighted criteria were those related to economic aspects, both fuel cost per unit of energy and capital investment required for the adaptation of each fuel technology, and the scalability and availability of infrastructure for all the available pathways. Similarly, on the paper published by (Ren & Lutzen, 2015), which targeted the emission reduction of shipping, the focus was on acidic emissions, mainly of sulphur oxides. The focus was more environmentally driven, weighting more the maturity of emission avoidance technology and the impact in emission reduction. The weighting is based on pair comparison, using fuzzy Analytical Hierarchy Process (AHP). (Ren & Liang, 2017) utilized the pair-wise comparison matrix by using linguistic variables, through a focus group of experts. The results show relatively increased importance in the economic criteria, primarily capital expenditure for technology adaptation, followed by fuel cost and environmental performance. At the work published by (Ren & Lutzen, 2017), a method assessing the alternatives under incomplete information is proposed, employing trapezoidal fuzzy numbers, replacing the commonly used, triangular fuzzy logic, claiming to be more accurate for expressing the preferences of the decision-makers in the cases where judgement is usually vague, subjective and ambiguous. Lastly, at the work presented by (van der Maas, 2020), using pairwise comparison the ranking demonstrates the relative importance of safety and fuel availability, while also focusing on scalability of production. The scope of the study is shifted towards port facilities and the viewpoint differs slightly into services and port infrastructure and potential benefit for the port activity and local communities.

As the variability in criteria ranking is evident through the literature review, in this study, the selected method is an alternation of conventional VIKOR method that makes use of incomplete criteria weights instead of AHP weighting methods, employed in literature. In addition to weight ranking scenarios, based on literature an entropy method for objective weights, is employed, for providing an additional ranking mechanism. The proposed VIKOR method ranks alternatives using the aggregated scores of alternatives computed by multiplying the extreme points of a set of criteria weights by the precise or interval consequences of alternatives. The methodology is demonstrated in the paper published by (Kim & Ahn, 2019). The incomplete criteria weight information could be based on one of the following types: (a) lower bounds, (b) weak inequalities, (c) ratio scale inequalities, (d) strict inequalities, and (e) weak inequalities of differences. The VIKOR method introduced by (Opricovic, 1998) is a method developed for multi-criteria optimization on complex systems. The VIKOR method is frequently compared with the technique for order performance by similarity to ideal solution, namely TOPSIS, introduced by (Hwang & Yoon, 1981), although they use a different aggregation function and a different normalization method. VIKOR focuses on selection ranking through a set of available alternatives in the presence of conflicting criteria by proposing a compromise solution based on the attributes of each alternative (Opricovic & Tzeng, 2004), providing a maximum function of utility based on the majority of the alternatives, while exploring the minimum of an individual regret compared to challengers (Opricovic & Tzeng, 2007). TOPSIS is sensitive to conflicting superiority, as it weighs equally the distance from the positive ideal solution and the farthest distance from the negative ideal solution, shifting focus to risk avoidance. Consequently, a cautious decision which selects to penalise relative risk would benefit from the methodology of TOPSIS. In the case of VIKOR, the objective to maximize profit is accompanied with a more flexible approach on individual regret, balancing the trade-off between them.

The VIKOR method has been extended to deal with various forms of uncertain data and incomplete information (Kim & Ahn, 2019). An extension of VIKOR method has been introduced by (Sayadi, et al., 2009) to deal with criteria set at interval numbers as input and that finally chooses the minimum of the aggregated intervals representing the closest distance to ideal solution, providing an external factor for optimism level of the decision maker. For the attributes of the problem studied at the current work, the uncertainty is originated from the variable weighting ranking found in literature. Thus, the alternative VIKOR method employed utilize the information provided by incomplete criteria weights instead of more strict and inflexible methods of weighting such as entropy for objective weights, AHP, or fuzzy formulation for subjective weights found in literature. The proposed VIKOR method ranks alternatives using the aggregated scores of alternatives computed by multiplying the extreme points of the set of criteria weights by the precise or interval consequences of alternatives.

VIKOR Method

In multicriteria problems setting, the decision maker considers a finite and discrete set of alternatives A = {A1 , A2 , …, Am}, each of which is evaluated for its performance in multiple criteria C = {C1 , C2 , …, Cn}. The respective score of each pair of criteria - alternative is denoted as f_{ij}, for all i alternatives available and for all j criteria. Score can be expressed as a value, as a linguistic term or value range depending on the problem formulation. Different scoring format require some extensions of the original method but could be handled efficiently.

$$\begin{array}{ccccc} & C1 & C2 & \ldots & Cn \\ A1 & f_{11} & f_{12} & \cdots & f_{1n} \\ A2 & f_{21} & \ddots & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ Am & f_{m1} & \ldots & \ldots & f_{mn} \end{array}$$

Table 10: Payoff table format

After concluding to the set of criteria, a set of criteria weights is denoted for each criterion. The weights are constrained as following:

$$\mathrm{W} = \sum_{1}^{\mathrm{n}} \mathrm{w}_j = 1, \text{while } \mathrm{w}_j \geq 0, \forall\, j \in \{1,2, \ldots \mathrm{n}\}$$

Development of the VIKOR method initiated with the following form of L_p - metric:

$$L_{pi} = \left\{ \sum_{j=1}^{n} \left| \frac{f_{ij} - f_j^*}{f_j^- - f_j^*} \right|^p \right\}^{1/p}$$

where $1 \leq p \leq \infty$.

Within the VIKOR methodology context, L_{1i} and $L_{\infty i}$ are used to formulate ranking measures, where L_{1i} denotes the maximum group utility, while the $L_{\infty i}$ expresses the individual regret point of view.

VIKOR methodology can be briefly described by the procedure arranged into five steps:

(a) Determine the best f_j^* and the worst f_j^- values of all criterion functions, $j = 1,2,\cdots,n$. If the ith function represents a benefit, then:

$$f_j^* = \max_i f_{ij} \text{ and } f_j^- = \min_i f_{ij}$$

While if it is a cost function:

$$f_j^* = \min_i f_{ij} \text{ and } f_j^- = \max_i f_{ij}$$

(b) Compute S_i (group utility) and R_i (individual regret) for each alternative:

$$S_i = \sum_{j=1}^{n} w_j\left(\left|f_j^* - f_{ij}/f_j^* - f_j^-\right|\right),\ \forall\ i \in \{1,2,\ldots m\}$$

$$R_i = \max_j w_j\left(\left|f_j^* - f_{ij}/f_j^* - f_j^-\right|\right),\ \forall\ i \in \{1,2,\ldots m\}$$

where w_j expresses the relative importance of each criterion by a quantified weights set.

(c) Compute the values Q_i, $i = 1,2,\ldots,m$ for each alternative by the relation:

$$Q_i = v\,(S_i - S^*)/(S^- - S^*) + (1-v)\,(R_i - R^*)/(R^- - R^*)$$

where,

$$S^* = \min_i S_i \text{ and } S^- = \max_i S_i$$
$$R^* = \min_i R_i \text{ and } R^- = \max_i R_i$$

The constant v, taking values in the range of [0,1], is the weight introduced to support the strategic preference between maximum group utility and individual regret; usually, $v = 0.5$, for evenly preference.

(d) Rank the alternatives by sorting the scores of S_i, R_i , and Q_i in descending order. The three resulting ranking lists are used to propose and validate a compromise solution (Opricovic & Tzeng, 2004).

(e) Propose as compromise solution the alternative, supposedly named a', which is ranked the best by the measure Q (minimum), while satisfying the below two conditions:

Condition 1 is the acceptable advantage, expressed as $Q(a'') - Q(a') \geq DQ$,
where a'' is the second-best alternative according to the Q ranking and DQ is calculated as $DQ = 1/(m-1)$; m is the number of alternatives assessed.

The 2nd condition is regarding the “acceptable stability in decision making’.

Alternative a' shall also be best ranked by S or/and R. This compromise solution is stable within a decision-making process, in one of the three categories; ‘‘voting by majority rule’’ when $v > 0.5$ is needed, or ‘‘by consensus’’ if $v \cong 0.5$, or ‘‘with veto’’ in the case of $v < 0.5$.

If the conditions are not met, a set of compromise solutions is proposed, which consists of:

- If condition 1 is not satisfied, alternatives $a', a'', \ldots, a^{(M)}$ are all considered superior selections and $a^{(M)}$ is determined as $Q(a^{(M)}) - Q(a') < DQ$ for maximum M. The alternatives are positioned “in closeness” to the dominant selection.
- If condition 2 is not satisfied a' and $a''$are both qualified as the dominant alternatives.

The best alternative(s), ranked by Q, is the one with the minimum value. The main ranking result is the compromise ranking list of alternatives, and the compromise solution with the ‘‘advantage rate’’. Ranking by VIKOR can be performed with different values of criteria weights, assessing the impact of criteria weights on the proposed set of compromise solution(s).

Extension of the VIKOR Method with Incomplete Information Criteria Weights

In the case of the present study, as the criteria weighting vary significantly, based on the researchers’ perspective and the composition of the experts’ team utilised for criteria weighting, the approach is extended to a variation of VIKOR assessing alternatives under incomplete criteria weights, provided a relative importance ranking.

The criteria weights are a critical component of the analysis and determine the final decision results. Different implementation of VIKOR methodology, reviewed in literature, has adopted ranging weighting methods with the prevalent being from precise or fuzzy; equal weighting (Chang, 2010), (Opricovic & Tzeng, 2004), (Opricovic, 2011), direct weighting (Kaya & Kahraman, 2010), employing the eigenvector method of the analytic hierarchy process (AHP) (Bazzazi, et al., 2011), or by following the entropy method described at (Liu & Wu, 2012). The entropy method (Xu, 2004), inspired from information theory, assigns a small weight to a criterion with comparable consequences, and a larger one on the criterion with varying attributes, as the latter assists more on differentiating alternatives to provide a solid ranking. Assessment of methodologies under incomplete weights are considered at (Kim & Ahn, 2019). The weight information falls under one of the following categories, to be contemplated under this framework.

- Lower bounds (LB): $W_{LB} = \{w: w_j \geq a_j > 0, j = 1, 2, \ldots, n\}$
- Weak inequalities (WI): $W_{WI} = \{w: w_1 \geq w_2 \geq \cdots \geq w_n \geq 0\}$
- Ratio scale inequalities (RI): $W_{RI} = \{w: w_1 \geq \alpha_1 w_2, \ldots., w_{n-1} \geq \alpha_{n-1} w_n,\ w_n \geq 0,\ \alpha_j > 0, \forall j\}$
- Strict inequalities (SI): $\mathrm{W}_{SI} = \{\mathrm{w}: \mathrm{w}_j - \mathrm{w}_{j+1} \geq \varepsilon_j > 0,\ \mathrm{j} = 1, 2, \ldots, \mathrm{n} - 1,\ \mathrm{w}_n \geq \varepsilon_n > 0\}$
- Weak inequalities of differences (WID): $W_{WID} = \{w: w_1 - w_2 \geq \cdots \geq w_{n-1} - w_n, w_n \geq 0\}$.

The weight information available for this study is formed under the weak inequalities scheme. The weight distribution found in literature provide two basic scenarios, which will be evaluated. Thirdly, a scenario based on the ranking resulting from entropy methodology (Bazzazi, et al., 2011) will be used. The purpose is to explore convergence of compromise solutions.

For this case, incomplete weights lead to a convex set from which we can identify multiple extreme points. Rearranging extreme points of the weak inequality set as a matrix $\mathbf{E} = (\boldsymbol{\lambda_1}, \boldsymbol{\lambda_2}, \dots, \boldsymbol{\lambda_n})$, where $\boldsymbol{\lambda_i}$ is the i^th column vector for which the elements are $1/i$ from the first to the i^th position, while the others are zeros. Presented as a matrix, it is rewritten as:

$$\boldsymbol{E} = \begin{bmatrix} 1 & 1/2 & \dots & 1/n \\ 0 & 1/2 & \dots & 1/n \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \dots & 1/n \end{bmatrix}$$

Then the single level of utility S_i, is reshaped into an interval with an upper and lower limit $S_i^U, and\ S_i^L$, respectively. Similarly, the individual regret R_i, is modified, based on upper and lower level into $R_i^U, and\ R_i^L$, considering the multiple extreme points of the incomplete weights set.

The set of equations can be expressed as:

$$S_i^U = max\{\boldsymbol{d}_i\boldsymbol{E}\}, S_i^L = min\{\boldsymbol{d}_i\boldsymbol{E}\}, i = 1, \cdots, m$$

$$R_i^U = \max_k\left\{\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}, R_i^L = \min_k\left\{\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\},\ i = 1, \cdots, m$$

where the normalized vector of consequences of the i^th alternative is $\boldsymbol{d}_i = \left(\frac{f_1^* - f_{i1}}{f_1^* - f_1^-}, \frac{f_2^* - f_{i2}}{f_2^* - f_2^-},\ \dots, \frac{f_n^* - f_{in}}{f_n^* - f_n^-}\right) \mid j \in I$ if associated with benefit criteria, while it is $\boldsymbol{d}_i = \left(\frac{f_{i1} - f_1^*}{f_1^- - f_1^*}, \frac{f_{i2} - f_2^*}{f_2^- - f_2^*},\ \dots, \frac{f_{in} - f_n^*}{f_n^- - f_n^*}\right) \mid j \in J$ if describing cost related criteria. I and J are the sets of indices associated with benefit and cost criteria respectively. As $\boldsymbol{E}$, we describe the matrix of extreme points of criteria weights, defined above and λ_{kj}, represents the j^th element of the k^th extreme point. Following this methodology, we derive into the intervals $[S_i^L, S_i^U]$ for group utility and the corresponding regret set at the interval $[R_i^L, R_i^U]$. The above lead to the computation of Q_i in an interval form $[Q_i^L, Q_i^U]$, for each $i = 1, \cdots, m$, by modifying the metrics definitions to be:

$$Q_i^L = v\,(S_i^L - S^*)/(S^- - S^*) + (1 - v)\,(R_i^L - R^*)/(R^- - R^*)$$

$$Q_i^U = v\,(S_i^U - S^*)/(S^- - S^*) + (1 - v)\,(R_i^U - R^*)/(R^- - R^*)$$

Entropy Weighting Method

Entropy weighting is a method used to determine the importance weights of decision attributes by directly relating a criterion's importance weighting to the information transmitted by that criterion (Bazzazi, et al., 2011), (Liu & Wu, 2012), (Chen & Li, 2010). Elaborating further, given a MCDM decision matrix with a column vector described as $f_j = (f_{1j}, f_{2j}, \dots, f_{mj})$ expressing the consequences of all alternatives in respect to j^{th} attribute. According to the methodology, the attribute has little importance, and thus corresponding weight, when all alternatives have similar outcomes for the same attribute.

Evidently, in the extreme case where all alternatives have the same evaluation in relation to a specific attribute, then that attribute shall be eliminated according to entropy methodology as it transmits no information about decision makers preferences. In contrast, the attribute that transmits the most information, providing the highest variability in the selected attribute, shall have the greatest importance in weighting. Expressing in mathematical terms, this translates into the projected outcomes of attribute j, P_{ij}, defined as:

$$P_{ij} = \frac{f_{ij}}{\sum_1^m f_{ij}}$$

The entropy is calculated as E_j on the set of projected outcomes of attribute j, following the formula below:

$$E_j = -\left(\frac{1}{\ln m}\right)\sum_{i=1}^{m} P_{ij} \ln P_{ij}$$

where m is the number of alternatives and E_j takes values within the interval $[0,1]$. The degree of diversification d_j of the consequences provided by outcomes of attribute j can be defined as $d_j = 1 - E_j$. Hence, the entropy weighting of any attribute is calculated as follows:

$$w_j = \frac{d_j}{\sum_1^m d_j}$$

In the cases where an a priori subjective weight is assigned to an attribute, namely λ_j, a computation of a compromise weighting, w_j^0, is provided to account both for the entropy weighting and the decision maker's/consortium of experts' subjective preference. The computation formula is expressed as:

$$w_j^0 = \frac{\lambda_j w_j}{\sum_1^m \lambda_j w_j}$$

This process combines the objective evaluation of weights, focusing on the attributes that differentiate the scores of the alternatives, while parallelly assessing the preference and subjective importance of criteria of the decision maker.

Implementation of VIKOR methodology with Incomplete Weights

Following the methodology described at the preceding section, the assessment of alternative marine fuels is performed. For the simplification of calculation, the below abbreviation is selected for the criteria described.

Category	**Criteria subcategory**	**Explanation**	**Abbreviation**	**Cost/ Benefit criteria**
Technical	Energy density	Volumetric (MJ/m^3)	T1	Benefit
Technical	Energy density	Per mass (MJ/kg)	T2	Benefit
Technical	Technological	Maturity (Propulsion)	T3	Benefit
Technical	Technological	Energy Efficiency	T4	Benefit
Environmental	GHG Emissions	WtW CO2e (grCO2e/KWh)	EN1	Cost
Environmental	Other local pollutants	Weighted Sox (gSOx/kWh), Nox (gNOx/kWh) and PM (gPM/kWh)	EN2	Cost
Economic	Capital per installed KW	CAPEX ($/kW)	EC1	Cost
Economic	Fuel Cost	Fuel cost ($/GJ)	EC2	Cost
Scalability	Scalability	Qualitative scale	SC1	Benefit
Safety	Flammability risk	Qualitative scale	SA1	Cost
Safety	Toxicity	Qualitative scale	SA2	Cost
Social	Social acceptance	Qualitative scale	SO1	Benefit

Table 11: List of criteria and abbreviations

Similarly, the alternatives are assigned to an abbreviation as presented below:

Fuel alternative	**Abbreviation**
Bio Diesel	A1
Bio LNG/ LBG	A2
Bio methanol	A3
e-Hydrogen (lq) -ICE	A4
e-methanol	A5
e-methane /e-LNG	A6
NH3	A7

Table 12: List of alternatives and abbreviations

Given the literature review, following a weighting process of the available studies (Hansson, et al., 2019), (Ren & Liang, 2017), (Ren & Lutzen, 2015), (Xing, et al., 2021), (Deniz & Zincir, 2015), (van der Maas, 2020) two scenarios of criteria ranking will be assessed under the incomplete weight set VIKOR methodology.

For the first ranking, safety-related are the dominant criteria, as the consortium of experts were mainly individuals with sea experience, which evaluate greatly safety, as it is a priority set by operators and managers for personnel serving onboard. At an environment with significant health and safety risks, adding potential risks through the fuel system and propulsion unit is a proposal that shall be carefully considered and mitigated in case of appliance.

Hence, the weight ranking firstly considered, from this point on referred as scenario 1 will be the following:

$$SA1 \geq SA2 \geq EN1 \geq EC2 \geq EC1 \geq SC1 \geq T1 \geq T2 \geq T4 \geq T3 \geq EN2 \geq SO1$$

The second ranking which will be considered is driven by the business proposal, financial aspects, and effectiveness of the potential alternative fuel path. Thus, focus is given on economic and environmental criteria. The corresponding ranking is given below:

$$EC2 \geq SC1 \geq EN1 \geq EC1 \geq SA1 \geq SA2 \geq T1 \geq T3 \geq SO1 \geq T2 \geq T4 \geq EN2$$

The third ranking is derived from the entropy methodology explained at the previous section. For this case two solvers will be employed. First, the ranking will be used as input to VIKOR extension with incomplete weights, while also the standard VIKOR methodology will be followed for the weight set resulting the entropy methodology calculation for criteria weights.

Based on the consequences per attribute, as repeated below, the sum of consequences per criteria - column is computed.

	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	34.0	44.0	3	0.24	50.1	1	600	26.4	4	2	0	0
A2	22.4	50.0	3	0.22	16.2	0.22	870	25.3	4	2	0	0
A3	15.9	20.1	2	0.24	15.1	0.08	617	19.2	3	2	2	2
A4	8.5	120.0	1	0.31	3.6	0.01	1810	42.5	2	1	4	0
A5	15.8	19.9	2	0.25	33.3	0.08	617	33.1	3	3	2	2
A6	22.4	50.0	3	0.22	28.5	0.22	870	31.9	4	3	0	0
A7	12.7	18.6	1	0.23	4.5	0.05	920	33.3	2	0	1	4
$\sum_{1}^{m} f_{ij}$	131.7	322.6	15	1.71	151.3	1.66	6304	211.7	22	13	9	8

Table 13: Alternatives consequences on the criteria selected

By normalising the terms to the projected outcome of each attribute, we derive the following results:

	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	0.26	0.14	0.18	0.14	0.33	0.60	0.10	0.12	0.17	0.15	0.06	0.07
A2	0.17	0.15	0.18	0.13	0.11	0.13	0.14	0.12	0.17	0.15	0.06	0.07
A3	0.12	0.06	0.14	0.14	0.10	0.05	0.10	0.09	0.14	0.15	0.19	0.20
A4	0.06	0.37	0.09	0.18	0.02	0.01	0.29	0.20	0.10	0.10	0.31	0.07

A5	0.12	0.06	0.14	0.15	0.22	0.05	0.10	0.16	0.14	0.20	0.19	0.20
A6	0.17	0.15	0.18	0.13	0.19	0.13	0.14	0.15	0.17	0.20	0.06	0.07
A7	0.10	0.06	0.09	0.13	0.03	0.03	0.15	0.16	0.10	0.05	0.13	0.33

Table 14: Normalised decision matrix

The entropy E_j is calculated on the set of projected outcomes of attribute j, according to Equation 16. The first term, $h = \frac{1}{ln\,m} = 0.514$, where m is the number of alternatives, which is seven at this case. The term to be summarised $P_{ij}\ ln\ P_{ij}$, per criterion, is given at the Table 15, along with the sum result and entropy calculation. Then, the degree of diversification is calculated. Finally, the weights are computed, according to Equation 18.

	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	-0.35	-0.27	-0.31	-0.28	-0.37	-0.31	-0.22	-0.26	-0.30	-0.28	-0.17	-0.18
A2	-0.30	-0.29	-0.31	-0.26	-0.24	-0.27	-0.27	-0.25	-0.30	-0.28	-0.17	-0.18
A3	-0.26	-0.17	-0.27	-0.28	-0.23	-0.15	-0.23	-0.22	-0.27	-0.28	-0.31	-0.32
A4	-0.18	-0.37	-0.22	-0.31	-0.09	-0.03	-0.36	-0.32	-0.23	-0.23	-0.36	-0.18
A5	-0.25	-0.17	-0.27	-0.28	-0.33	-0.15	-0.23	-0.29	-0.27	-0.32	-0.31	-0.32
A6	-0.30	-0.29	-0.31	-0.26	-0.31	-0.27	-0.27	-0.29	-0.30	-0.32	-0.17	-0.18
A7	-0.23	-0.16	-0.22	-0.27	-0.11	-0.11	-0.28	-0.29	-0.23	-0.15	-0.26	-0.37
$\sum_{i=1}^{m} P_{ij}\ ln\ P_{ij}$	-1.86	-1.73	-1.91	-1.94	-1.68	-1.27	-1.86	-1.92	-1.93	-1.88	-1.77	-1.73
E_j	0.96	0.89	0.98	1.00	0.86	0.65	0.96	0.99	0.99	0.96	0.91	0.89
d_j	0.04	0.11	0.02	0.00	0.14	0.35	0.04	0.01	0.01	0.04	0.09	0.11
w_j	0.04	0.12	0.02	0.00	0.14	0.36	0.04	0.01	0.01	0.04	0.09	0.11
rank	6	3	9	12	2	1	7	10	11	8	5	4

Table 15: Entropy method weighting matrix

Weighting Scenario 1

The weights ranking to be considered at first, is the following:

$$SA1 \geq SA2 \geq EN1 \geq EC2 \geq EC1 \geq SC1 \geq T1 \geq T2 \geq T4 \geq T3 \geq EN2 \geq SO1$$

Scenario 1 ranking's dominant criteria are related to safety of operation and secondly, the environmental impact in terms of GHG emissions and the economic aspects of the alternatives. Providing the initial decision table, the computation of f_j^* and f_j^-, is performed according to (5) and (6).

	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	34.0	44.0	4	0.24	50.1	1	600	26.4	4	2	0	0
A2	22.4	50.0	4	0.22	16.2	0.22	870	25.3	4	2	0	0

A3	15.9	20.1	3	0.24	15.1	0.08	617	19.2	3	2	2	2
A4	8.5	120.0	2	0.31	3.6	0.01	1810	42.5	2	1	4	0
A5	15.8	19.9	3	0.25	33.3	0.08	617	33.1	3	3	2	2
A6	22.4	50.0	4	0.22	28.5	0.22	870	31.9	4	3	0	0
A7	12.7	18.6	2	0.23	4.5	0.05	920	33.3	2	0	2	4
f_i^*	34	120	4	0.31	3.6	0.01	600	19.2	4	3	0	0
f_i^-	8.5	18.6	2	0.22	50.1	1	1810	42.5	2	0	4	4

Table 16: Determination of best and worst consequences per criterion

Proceeding with normalising consequences, vectors d_i and ranking according to the incomplete weighting are provided

d_i	SA1	SA2	EN1	EC2	EC1	SC1	T1	T2	T4	T3	EN2	SO1
A1	0.00	0.00	1.00	0.31	0.00	0.00	0.00	0.75	0.79	0.00	1.00	0.33
A2	0.00	0.00	0.27	0.26	0.22	0.00	0.45	0.69	1.00	0.00	0.21	0.33
A3	0.50	0.50	0.25	0.00	0.01	0.50	0.71	0.99	0.79	0.50	0.07	0.33
A4	1.00	0.00	0.00	1.00	1.00	1.00	1.00	0.00	0.00	1.00	0.00	0.67
A5	0.50	0.50	0.64	0.60	0.01	0.50	0.71	0.99	0.68	0.50	0.07	0.00
A6	0.00	0.00	0.54	0.55	0.22	0.00	0.45	0.69	1.00	0.00	0.21	0.00
A7	0.25	1.00	0.02	0.61	0.26	1.00	0.84	1.00	0.94	1.00	0.04	1.00

Table 17: Normalised decision matrix sorted by criteria weights ranking

The matrix $E = (\lambda_1, \lambda_2, \ldots, \lambda_n)$, where λ_i is the ith column vector, is modified to be the following, based on the 12 criteria employed.

$$E = \begin{bmatrix} 1 & 1/2 & 1/3 & \ldots & 1/12 \\ 0 & 1/2 & 1/3 & \ldots & 1/12 \\ 0 & 0 & 1/3 & \ldots & 1/12 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1/12 \end{bmatrix}$$

Hence, the $\boldsymbol{d} \cdot \boldsymbol{E}$ vectors are exactly:

$d_i * E$												
A1	0.00	0.00	0.33	0.33	0.26	0.22	0.19	0.26	0.32	0.28	0.35	0.35
A2	0.00	0.00	0.09	0.13	0.15	0.13	0.17	0.24	0.32	0.29	0.28	0.29
A3	0.50	0.50	0.42	0.31	0.25	0.29	0.35	0.43	0.47	0.47	0.44	0.43
A4	1.00	0.50	0.33	0.50	0.60	0.67	0.71	0.63	0.56	0.60	0.55	0.56
A5	0.50	0.50	0.55	0.56	0.45	0.46	0.49	0.56	0.57	0.56	0.52	0.48
A6	0.00	0.00	0.18	0.27	0.26	0.22	0.25	0.31	0.38	0.35	0.33	0.31
A7	0.25	0.63	0.42	0.47	0.43	0.52	0.57	0.62	0.66	0.69	0.63	0.66

Table 18: The value Si for precise consequences and incomplete weights

while the $\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}$ factor is visualised at the Table 19 given below:

$\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}$											
A1	0.00	0.00	0.33	0.08	0.00	0.00	0.00	0.09	0.09	0.00	0.09	0.03
A2	0.00	0.00	0.09	0.07	0.04	0.00	0.06	0.09	0.11	0.00	0.02	0.03
A3	0.50	0.25	0.08	0.00	0.00	0.08	0.10	0.12	0.09	0.05	0.01	0.03
A4	1.00	0.00	0.00	0.25	0.20	0.17	0.14	0.00	0.00	0.10	0.00	0.06
A5	0.50	0.25	0.21	0.15	0.00	0.08	0.10	0.12	0.08	0.05	0.01	0.00
A6	0.00	0.00	0.18	0.14	0.04	0.00	0.06	0.09	0.11	0.00	0.02	0.00
A7	0.25	0.50	0.01	0.15	0.05	0.17	0.12	0.13	0.10	0.10	0.00	0.08

Table 19: Regret matrix

and the corresponding $S_i^U = max\{\boldsymbol{d}_i\boldsymbol{E}\}$, $S_i^L = min\{\boldsymbol{d}_i\boldsymbol{E}\}$, $R_i^U = \max_k\left\{\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}$, $R_i^L = \min_k\left\{\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}$, $\forall i = 1, \cdots, m$ for each alternative are following:

Alternatives	A1	A2	A3	A4	A5	A6	A7
S_i^U	0.35	0.32	0.50	1.00	0.57	0.38	0.69
S_i^L	0.00	0.00	0.25	0.33	0.45	0.00	0.25
R_i^U	0.33	0.11	0.50	1.00	0.50	0.18	0.50
R_i^L	0	0	0	0	0	0	0.004

Table 20: Assessment of alternatives through Si and Qi

Based on the above, the boundaries are calculated as:

$$S^* = \min_i S_i^L = 0 \text{ and } S^- = \max_i S_i^U = 1$$
$$R^* = \min_i R_i^L = 0 \text{ and } R^- = \max_i R_i^U = 1$$

Computing intervals $[Q_i^L, Q_i^U]$, for $i = 1, \cdots, 7$, using equal weighting-optimism factor of $v = 0.5$ yields Table 21:

Alternatives	A1	A2	A3	A4	A5	A6	A7
Q_i^U	0.34	0.22	0.50	1.00	0.53	0.28	0.60
Q_i^L	0.00	0.00	0.13	0.17	0.22	0.00	0.13

Table 21: Q values

Visualising the rank based on $[Q_i^L, Q_i^U]$, the result is the following:

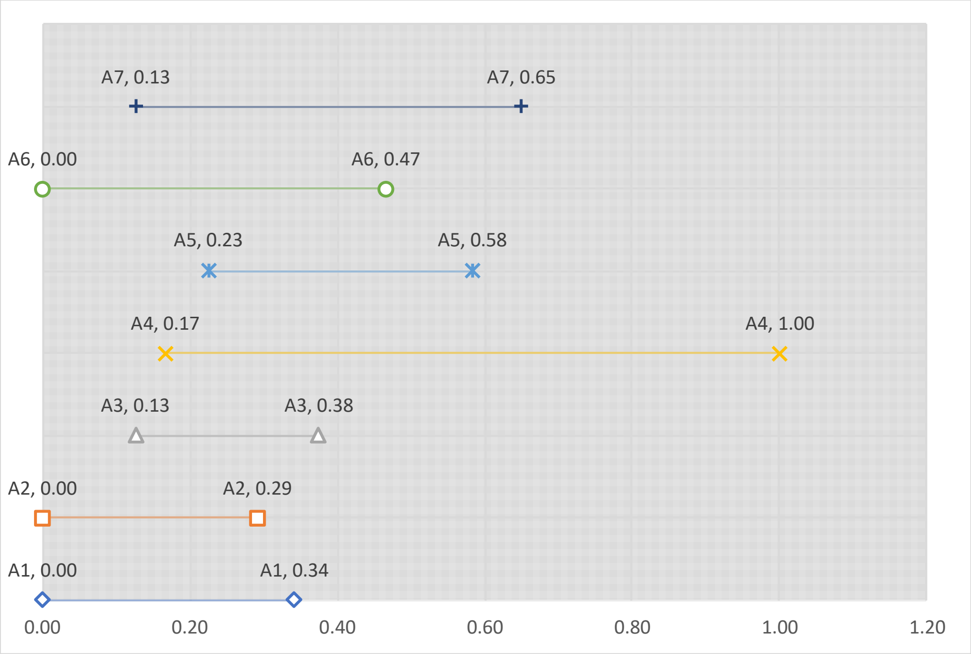

Figure 4: Proposed compromise solution

Additionally plotting group utility, $[S_i^L, S_i^U]$,

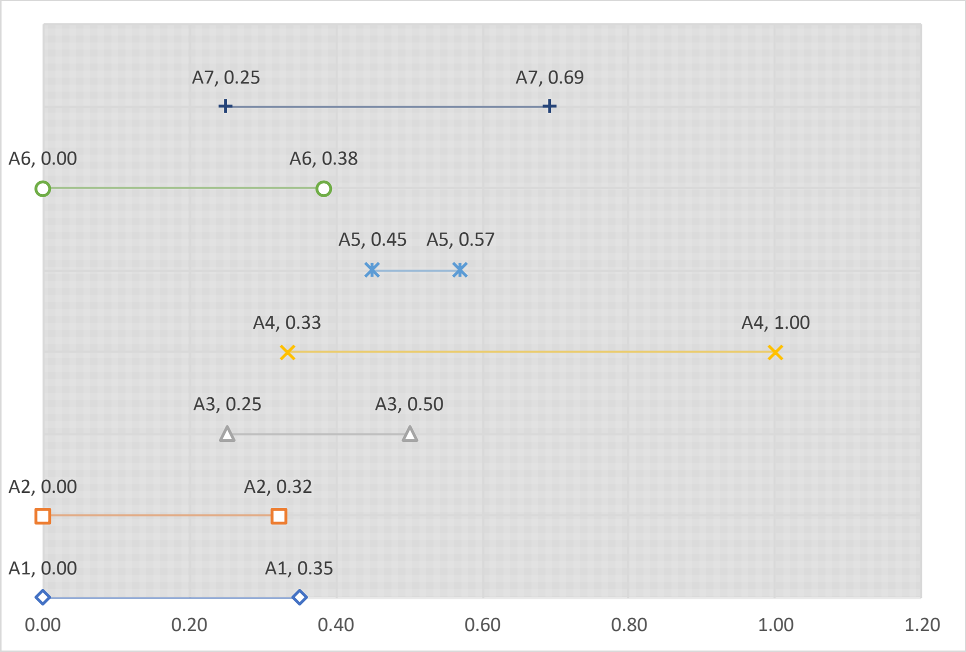

Figure 5: Group utility

we conclude to the superiority of A2 alternative, bio-LNG/liquified biogas.

The ranking, based on the midpoint of interval $[Q_i^L, Q_i^U]$, is:

$$A2 > A1 > A6 > A3 > A7 > A5 > A4$$

With the selected criteria weights ranking, an assessment of sensitivity based on the optimism factor is performed.

At range of values of $v \in [0,1]$, the compromise solution is changing based on the optimism factor. At the dominant R range, where regret is considered, $v = 0$, $A3$ alternative, bio methanol is superior. For $v \in [0.1,1]$, compromise solution is stable and $A2$ is selected.

Weighting Scenario 2

The weight ranking to be considered in this case, is the following:

$$EC2 \geq SC1 \geq EN1 \geq EC1 \geq SA1 \geq SA2 \geq T1 \geq T3 \geq SO1 \geq T2 \geq T4 \geq EN2$$

Scenario 2 ranking's dominant criteria are related to economic criteria and scalability and applicability of the solution proposed, followed by the environmental impact in terms of GHG emissions. Proceeding with normalising consequences, vectors d_i and ranking according to the incomplete weighting are provided:

d_i	EC2	SC1	EN1	EC1	SA1	SA2	T1	T3	SO1	T2	T4	EN2
A1	0.31	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.33	0.75	0.79	1.00
A2	0.26	0.00	0.27	0.22	0.00	0.00	0.45	0.00	0.33	0.69	1.00	0.21
A3	0.00	0.50	0.25	0.01	0.50	0.50	0.71	0.50	0.33	0.99	0.79	0.07
A4	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.67	0.00	0.00	0.00
A5	0.60	0.50	0.64	0.01	0.50	0.50	0.71	0.50	0.00	0.99	0.68	0.07
A6	0.55	0.00	0.54	0.22	0.00	0.00	0.45	0.00	0.00	0.69	1.00	0.21
A7	0.61	1.00	0.02	0.26	0.25	1.00	0.84	1.00	1.00	1.00	0.94	0.04

Table 22: Normalised decision matrix ordered by criteria weights ranking

The matrix $E = (\lambda_1, \lambda_2, \dots, \lambda_n)$, where λ_i is the i$^{\text{th}}$ column vector, is modified to be the following, based on the 12 criteria employed.

$$E = \begin{bmatrix} 1 & 1/2 & 1/3 & \dots & 1/12 \\ 0 & 1/2 & 1/3 & \dots & 1/12 \\ 0 & 0 & 1/3 & \dots & 1/12 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1/12 \end{bmatrix}$$

Hence, $\boldsymbol{d} \cdot \boldsymbol{E}$ can be calculated as in Table 23:

$d_i * E$												
A1	0.31	0.15	0.44	0.33	0.26	0.22	0.19	0.16	0.18	0.24	0.29	0.35
A2	0.26	0.13	0.18	0.19	0.15	0.13	0.17	0.15	0.17	0.22	0.29	0.29
A3	0.00	0.25	0.25	0.19	0.25	0.29	0.35	0.37	0.37	0.43	0.46	0.43
A4	1.00	1.00	0.67	0.75	0.80	0.67	0.71	0.75	0.74	0.67	0.61	0.56
A5	0.60	0.55	0.58	0.44	0.45	0.46	0.49	0.50	0.44	0.49	0.51	0.48
A6	0.55	0.27	0.36	0.33	0.26	0.22	0.25	0.22	0.20	0.25	0.31	0.31
A7	0.61	0.80	0.54	0.47	0.43	0.52	0.57	0.62	0.66	0.70	0.72	0.66

Table 23: The value Si for precise consequences and incomplete weights

while the $\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}$ factor is visualised at Table 24 given below:

$\max\limits_{j}\{d_{ij}\boldsymbol{\lambda_{kj}}\}$											
A1	0.31	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.04	0.07	0.07	0.08
A2	0.26	0.00	0.09	0.06	0.00	0.00	0.06	0.00	0.04	0.07	0.09	0.02
A3	0.00	0.25	0.08	0.00	0.10	0.08	0.10	0.06	0.04	0.10	0.07	0.01
A4	1.00	0.50	0.00	0.25	0.20	0.00	0.14	0.13	0.07	0.00	0.00	0.00
A5	0.60	0.25	0.21	0.00	0.10	0.08	0.10	0.06	0.00	0.10	0.06	0.01
A6	0.55	0.00	0.18	0.06	0.00	0.00	0.06	0.00	0.00	0.07	0.09	0.02
A7	0.61	0.50	0.01	0.07	0.05	0.17	0.12	0.13	0.11	0.10	0.09	0.00

Table 24: Regret matrix

and the corresponding $S_i^U = max\{\boldsymbol{d}_i\boldsymbol{E}\}$, $S_i^L = min\{\boldsymbol{d}_i\boldsymbol{E}\}$, $R_i^U = \max\limits_{k}\left\{\max\limits_{j}\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}$, $R_i^L = \min\limits_{k}\left\{\max\limits_{j}\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}$, $\forall i = 1, \cdots, m$, follow in Table 25:

Alternatives	A1	A2	A3	A4	A5	A6	A7
S_i^U	0.44	0.29	0.46	1.00	0.60	0.55	0.80
S_i^L	0.15	0.13	0.00	0.56	0.44	0.20	0.43
R_i^U	0.33	0.26	0.25	1.00	0.60	0.55	0.61
R_i^L	0	0	0	0	0	0	0.003

Table 25: Si and Qi interval values

Based on the above, the boundaries are calculated as:

$$S^* = \min_i S_i^L = 0 \text{ and } S^- = \max_i S_i^U = 1$$
$$R^* = \min_i R_i^L = 0 \text{ and } R^- = \max_i R_i^U = 1$$

Computation of $[Q_i^L, Q_i^U]$ intervals, for $i = 1, \cdots, 7$, using equal weighting-optimism factor of $v = 0.5$, is presented in Table 26.

Alternatives	A1	A2	A3	A4	A5	A6	A7
Q_i^U	0.38	0.28	0.36	1.00	0.60	0.55	0.71
Q_i^L	0.08	0.06	0.00	0.28	0.22	0.10	0.22

Table 26: Q interval values

Visualising the rank based on $[Q_i^L, Q_i^U]$, the result is the following:

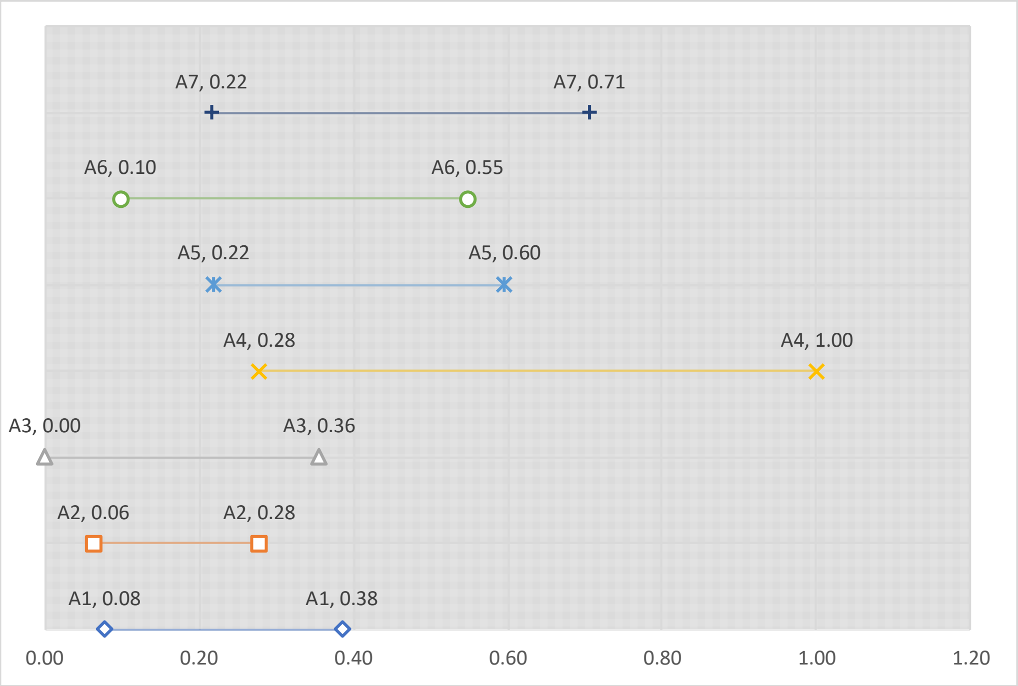

Figure 6: Proposed compromise solution

Additionally, the plot of group utility, $[S_i^L, S_i^U]$ measure is presented in Figure 7.

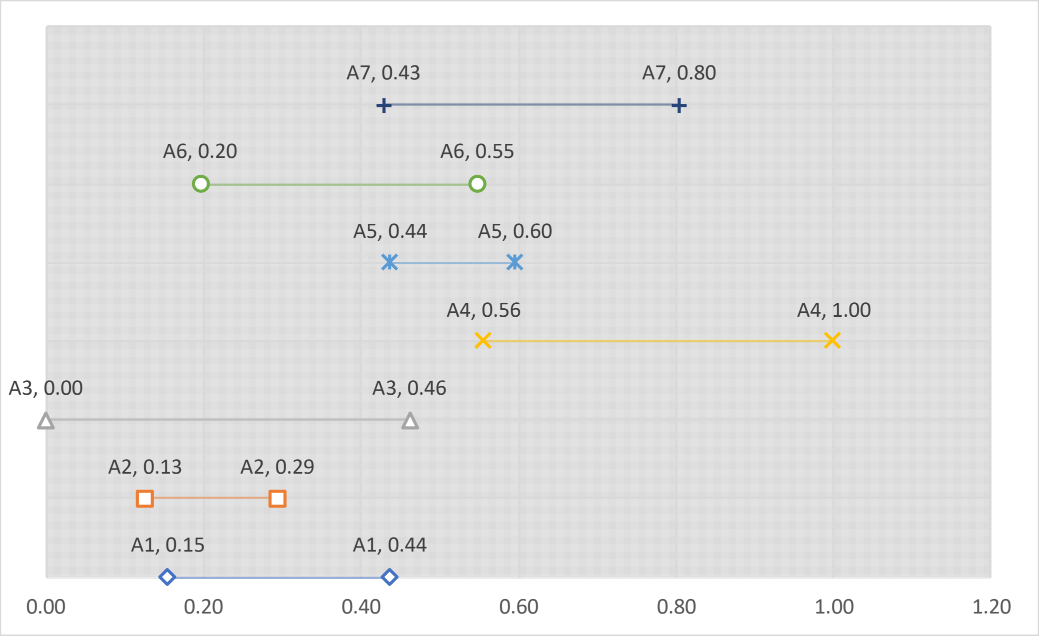

Figure 7: Group utility interval values

Again, similarly to Scenario 1, the result is that A2 alternative is superior, bio-LNG/liquified biogas, thus presenting a rather robust behaviour in terms of weighting preferences.

The ranking, based on the midpoints of intervals $[Q_i^L, Q_i^U]$, is exactly:

$$A2 > A3 > A1 > A6 > A5 > A7 > A4$$

At range of values of $v \in [0,1]$, the compromise solution is changing based on the optimism factor. At the dominant R range, where individual regret is considered, $v \in [0,0.2]$, $A3$ alternative, bio methanol is superior. For $v \in [0.2,1]$, compromise solution is stable and $A2$ is selected.

Entropy Weighting Method Results

As explained at the entropy weighting methodology section, the attribute that transmits the most information, providing the highest variability in the selected attribute, is weighted with the highest weight, thus having the highest importance. Implementing the normalisation, by using the formula $P_{ij} = \frac{f_{ij}}{\sum_1^m f_{ij}}$, results in Table 27:

	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	0.26	0.14	0.18	0.14	0.33	0.60	0.10	0.12	0.17	0.15	0.06	0.07
A2	0.17	0.15	0.18	0.13	0.11	0.13	0.14	0.12	0.17	0.15	0.06	0.07
A3	0.12	0.06	0.14	0.14	0.10	0.05	0.10	0.09	0.14	0.15	0.19	0.20
A4	0.06	0.37	0.09	0.18	0.02	0.01	0.29	0.20	0.10	0.10	0.31	0.07
A5	0.12	0.06	0.14	0.15	0.22	0.05	0.10	0.16	0.14	0.20	0.19	0.20
A6	0.17	0.15	0.18	0.13	0.19	0.13	0.14	0.15	0.17	0.20	0.06	0.07
A7	0.10	0.06	0.09	0.13	0.03	0.03	0.15	0.16	0.10	0.05	0.13	0.33

Table 27: Normalisation process

Then, the entropy is calculated as E_j on the set of the projected outcomes of attribute j, following the formula $E_j = -\left(\frac{1}{\ln m}\right)\sum_{i=1}^{m} P_{ij} \ln P_{ij}$, where m is the number of alternatives and E_j takes values within the interval $[0,1]$. The degree of diversification d_j of the consequences is computed by the outcomes of attribute j, which is defined as $d_j = 1 - E_j$. Lastly, the entropy weighting of any attribute is calculated by $w_j = \frac{d_j}{\sum_1^m d_j}$. The calculations are demonstrated, along with the ranking in Table 28:

$P_{ij} \ln P_{ij}$	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	-0.35	-0.27	-0.31	-0.28	-0.37	-0.31	-0.22	-0.26	-0.30	-0.28	-0.17	-0.18
A2	-0.30	-0.29	-0.31	-0.26	-0.24	-0.27	-0.27	-0.25	-0.30	-0.28	-0.17	-0.18
A3	-0.26	-0.17	-0.27	-0.28	-0.23	-0.15	-0.23	-0.22	-0.27	-0.28	-0.31	-0.32
A4	-0.18	-0.37	-0.22	-0.31	-0.09	-0.03	-0.36	-0.32	-0.23	-0.23	-0.36	-0.18
A5	-0.25	-0.17	-0.27	-0.28	-0.33	-0.15	-0.23	-0.29	-0.27	-0.32	-0.31	-0.32
A6	-0.30	-0.29	-0.31	-0.26	-0.31	-0.27	-0.27	-0.29	-0.30	-0.32	-0.17	-0.18
A7	-0.23	-0.16	-0.22	-0.27	-0.11	-0.11	-0.28	-0.29	-0.23	-0.15	-0.26	-0.37

$\sum_{i=1}^{m} P_{ij} \ln P_{ij}$	-1.86	-1.73	-1.91	-1.94	-1.68	-1.27	-1.86	-1.92	-1.93	-1.88	-1.77	-1.73
E_j	0.96	0.89	0.98	1.00	0.86	0.65	0.96	0.99	0.99	0.96	0.91	0.89
d_j	0.04	0.11	0.02	0.00	0.14	0.35	0.04	0.01	0.01	0.04	0.09	0.11
w_j	0.04	0.12	0.02	0.00	0.14	0.36	0.04	0.01	0.01	0.04	0.09	0.11
$Ranking$	6	3	9	12	2	1	7	10	11	8	5	4

Table 28: Entropy weight calculation and criteria weight ranking

Weighting Scenario 3

The weight ranking provided by the entropy weighting procedure is the following:

$$EN2 \geq EN1 \geq T2 \geq SA2 \geq SA1 \geq T1 \geq EC1 \geq SO1 \geq T3 \geq EC2 \geq SC1 \geq T4$$

The ranking categories are mixed, but the dominant criteria are related to the environmental impact.

Proceeding with normalising consequences, vectors d_i and ranking according to the incomplete weighting are presented in Table 29:

d_i	EN2	EN1	T2	SA2	SA1	T1	EC1	SO1	T3	EC2	SC1	T4
A1	1.00	1.00	0.75	0.00	0.00	0.00	0.00	0.33	0.00	0.31	0.00	0.79
A2	0.21	0.27	0.69	0.00	0.00	0.45	0.22	0.33	0.00	0.26	0.00	1.00
A3	0.07	0.25	0.99	0.50	0.50	0.71	0.01	0.33	0.50	0.00	0.50	0.79
A4	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.67	1.00	1.00	1.00	0.00
A5	0.07	0.64	0.99	0.50	0.50	0.71	0.01	0.00	0.50	0.60	0.50	0.68
A6	0.21	0.54	0.69	0.00	0.00	0.45	0.22	0.00	0.00	0.55	0.00	1.00
A7	0.04	0.02	1.00	1.00	0.25	0.84	0.26	1.00	1.00	0.61	1.00	0.94

Table 29: Normalised decision matrix sorted by criteria weight ranking

As in the previous scenarios, the matrix $E = (\lambda_1, \lambda_2, \dots, \lambda_n)$, where λ_i is the ith column vector, is the same, and modified based on the 12 criteria employed.

$$E = \begin{bmatrix} 1 & 1/2 & 1/3 & \dots & 1/12 \\ 0 & 1/2 & 1/3 & \dots & 1/12 \\ 0 & 0 & 1/3 & \dots & 1/12 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1/12 \end{bmatrix}$$

Computation of $\boldsymbol{d} \cdot \boldsymbol{E}$ is presented in Table 30:

$d_i * E$												
A1	1.00	1.00	0.92	0.69	0.55	0.46	0.39	0.39	0.34	0.34	0.31	0.35
A2	0.21	0.24	0.39	0.29	0.23	0.27	0.26	0.27	0.24	0.24	0.22	0.29
A3	0.07	0.16	0.43	0.45	0.46	0.50	0.43	0.42	0.43	0.39	0.40	0.43

A4	0.00	0.00	0.00	0.00	0.20	0.33	0.43	0.46	0.52	0.57	0.61	0.56
A5	0.07	0.35	0.57	0.55	0.54	0.57	0.49	0.43	0.44	0.45	0.46	0.48
A6	0.21	0.37	0.48	0.36	0.29	0.32	0.30	0.26	0.24	0.27	0.24	0.31
A7	0.04	0.03	0.35	0.52	0.46	0.52	0.49	0.55	0.60	0.60	0.64	0.66

Table 30: Normalized regret vector values on the extreme points

while the $\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}$ factor is shown in Table 31:

$\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}$												
A1	1.00	0.50	0.25	0.00	0.00	0.00	0.00	0.04	0.00	0.03	0.00	0.07
A2	0.21	0.14	0.23	0.00	0.00	0.08	0.03	0.04	0.00	0.03	0.00	0.08
A3	0.07	0.12	0.33	0.13	0.10	0.12	0.00	0.04	0.06	0.00	0.05	0.07
A4	0.00	0.00	0.00	0.00	0.20	0.17	0.14	0.08	0.11	0.10	0.09	0.00
A5	0.07	0.32	0.33	0.13	0.10	0.12	0.00	0.00	0.06	0.06	0.05	0.06
A6	0.21	0.27	0.23	0.00	0.00	0.08	0.03	0.00	0.00	0.05	0.00	0.08
A7	0.04	0.01	0.33	0.25	0.05	0.14	0.04	0.13	0.11	0.06	0.09	0.08

Table 31: Maximum regret values

while, the corresponding $S_i^U = max\{\boldsymbol{d}_i\boldsymbol{E}\}$, $S_i^L = min\{\boldsymbol{d}_i\boldsymbol{E}\}$, $R_i^U = \max_k\left\{\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}$, $R_i^L = \min_k\left\{\max_j\{d_{ij}\boldsymbol{\lambda_{kj}}\}\right\}$, $\forall i = 1,\cdots,m$, are summarised in Table 32:

Alternatives	A1	A2	A3	A4	A5	A6	A7
S_i^U	1.00	0.39	0.50	0.61	0.57	0.48	0.66
S_i^L	0.31	0.21	0.07	0.00	0.07	0.21	0.03
R_i^U	1.00	0.23	0.33	0.20	0.33	0.27	0.33
R_i^L	0.00	0.00	0.00	0.00	0.00	0.00	0.01

Table 32: S and Q interval values

Based on the above, the boundaries are calculated as:

$$S^* = \min_i S_i^L = 0 \text{ and } S^- = \max_i S_i^U = 1$$
$$R^* = \min_i R_i^L = 0 \text{ and } R^- = \max_i R_i^U = 1$$

Computation of $[Q_i^L, Q_i^U]$ intervals, for $i = 1,\cdots,7$, using equal weighting-optimism factor of $v = 0.5$, is presented in Table 33.

Alternatives	A1	A2	A3	A4	A5	A6	A7
Q_i^U	1.00	0.31	0.42	0.40	0.45	0.37	0.50
Q_i^L	0.15	0.11	0.04	0.00	0.04	0.11	0.02

Table 33: Q interval values

Visualising the rank, based on $[Q_i^L, Q_i^U]$, result in Figure 8.

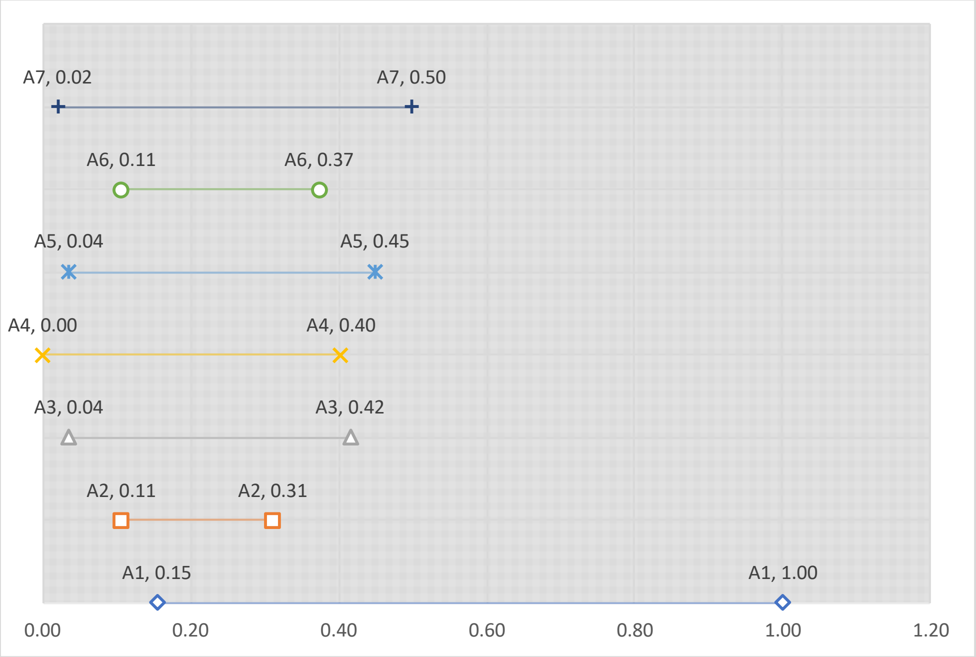

Figure 8: Proposed compromise solution

Additionally, the plot of group utility measure $[S_i^L, S_i^U]$ is presented in Figure 9.

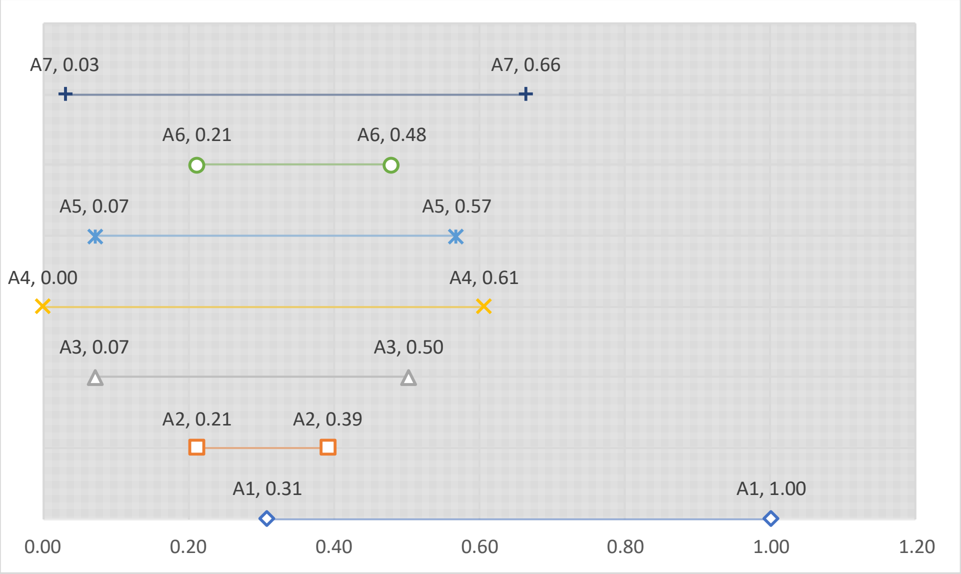

Figure 9: Group utility measure

The result reveals the superiority of $A4$ alternative (Hydrogen solution), followed by $A2$ (bio-LNG/liquified biogas solution). This result is strongly related to the increased importance of environmental performance criteria, local pollutants and GHG emission, in which hydrogen produced through renewable energy, and green processes is assigned with the best scores.

The full ranking based on the midpoint of interval $[Q_i^L, Q_i^U]$, is exactly:

$$A4 > A2 > A3 > A6 > A5 > A7 > A1$$

With the selected criteria weighting, a sensitivity analysis regarding the optimism factor shows a rather stable superiority of $A4$, on the range of values of $v \in [0, 0.75]$. At the dominant S range, where group utility is considered, that is $v \in [0.75, 1]$, $A3$ alternative (bio methanol solution) is preferred.

VIKOR Application In Conjunction With Entropy Method Based Weighting

Following the weighting computed through the entropy method, at Table 28, the conventional VIKOR is applied on the emerged weights.

Computation of the normalising consequences in terms of vectors d_i are presented in Table 34.

d_i	T1	T2	T3	T4	EN1	EN2	EC1	EC2	SC1	SO1	SA1	SA2
A1	0.00	0.75	0.00	0.79	1.00	1.00	0.00	0.31	0.00	0.33	0.00	0.00
A2	0.45	0.69	0.00	1.00	0.27	0.21	0.22	0.26	0.00	0.33	0.00	0.00
A3	0.71	0.99	0.50	0.79	0.25	0.07	0.01	0.00	0.50	0.33	0.50	0.50
A4	1.00	0.00	1.00	0.00	0.00	0.00	1.00	1.00	1.00	0.67	1.00	0.00
A5	0.71	0.99	0.50	0.68	0.64	0.07	0.01	0.60	0.50	0.00	0.50	0.50
A6	0.45	0.69	0.00	1.00	0.54	0.21	0.22	0.55	0.00	0.00	0.00	0.00
A7	0.84	1.00	1.00	0.94	0.02	0.04	0.26	0.61	1.00	1.00	0.25	1.00

Table 34: Normalised decision table

Following, the calculation of group utility, individual regret, and their convex normalised combination in terms of Q measure, result in the alternatives ranking as visualised in Figures 10 to 12 for the three points of view.

Figure 10: Group utility ranking within the VIKOR framework

Figure 11: Individual regret ranking within the VIKOR framework

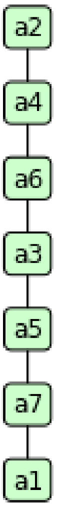

Figure 12: Compromise solution ranking within the VIKOR framework

The result partly matches with the ranking of the Scenario 3, which is VIKOR with incomplete weights, sorted under weak inequality by the entropy method. The result shows the superiority of A2 alternative (bio-LNG/LBG solution), also agreeing with the two scenarios assessed prior; followed by A4; which is Green Hydrogen solution, performing best at the highly rated environmental criteria.

The full ranking, based on the Q_i values, is now:

$$A2 > A4 > A6 > A3 > A5 > A7 > A1$$

With the selected criteria weights ranking, a sensitivity analysis based on the optimism factor is performed. On the entire range of values of $v \in [0.1]$, $A2$ remains the superior solution, thus presenting a rather robust behaviour against strategy coefficient selection

Lastly, we explore the closeness and stability conditions of the compromise solution A2, which is ranked the best in terms of measure Q (minimum). Indeed, the stability condition is satisfied, as alternative A2 is ranked first both at the individual regret and group utility lists.

Investigating acceptable advantage condition, $DQ = 1/(m-1)$ has to first to be computed, where m stands for the number of alternatives assessed. In our case, we have $DQ = 1/6 = 0.167$.

Calculating the closeness of A2 with the following best solution in terms of Q (A4), we obtain $Q(a'') - Q(a') = Q(A4) - Q(A2) = 0.009 < 0.167$. Hence, the acceptance advantage condition is not met. Thus, a compromise solution set should be proposed withing the VIKOR framework approach. In particular, we should select the best M solutions in terms of Q values, where M is is determined by the inequality $Q(AM) - Q(A2) < DQ$, for the maximum value it holds. We have:

$$Q(A6) - Q(A2) = 0.082 < 0.167$$

$$Q(A3) - Q(A2) = 0.264 > 0.167$$

This means that alternatives $A2, A4\ and\ A6$, namely bio-LNG, e-Hydrogen and e-LNG solutions, are positioned “in closeness” and constitute the compromise solution set, as presented in Figure 13.

Figure 13: The VIKOR compromise solution set.

Conclusions, Discussion and Further Research Perspectives

Assessing alternative pathways to decarbonise shipping is a multiparametric problem, which entails various forms of uncertainty in many aspects. The criteria selection is broad, and the importance of each attribute differs, based on the consortium of experts and their viewpoint. Providing a concrete framework to accommodate a sophisticated technique, such as a MCDM approach, is essential, while similar applications in maritime sector are limited. At this study, seven long term fuel alternatives for shipping decarbonisation are assessed under twelve criteria, covering many aspects of consideration. The criteria range from numerical, quantitative measures to qualitative attributes. The VIKOR methodology has been employed to evaluate the fuel alternatives. Based on the literature review, criteria weights do not converge to a single viewpoint. Hence, the approach selected was to use incomplete weights, by adopting weak inequality ranking. To cover a multiple perspective, three weight scenario rankings were assessed. The first scenario is driven by the criteria related to safety operation, followed by the climate impact and the economic aspect. At the second scenario, the importance of economic aspects is dominant, followed by the climate impact and the scalability of the solution proposed. Lastly, by using the entropy methodology for computing criteria weights, the conventional VIKOR was employed to provide the ranking of alternatives, while the weights were sorted and used under the incomplete weight framework to provide the third weights ranking scenario. Both Scenarios 1 and 2, as well as the conventional VIKOR implementation, conclude to the alternative of bio-LNG, or liquid biogas as the superior alternative. As the safety of operation is secured, similar systems powered by fossil LNG are operational at scale, providing the required know-how, while achieving competitive economics and substantial GHG emission reduction. This pathway is followed by many companies and operators, especially, at the initial stage of the transition posing excessive demand for trained seafarers (Martin, 2022). At the 3rd scenario, bio-LNG is also evaluated as one of the top alternatives, but as the weights of climate impact criteria are dominant, green hydrogen, produced by processes powered by renewable electricity, is the superior choice. Bio-methanol is very competitive in all scenarios, being preferred marginally only at extreme regret dominant environments. Some majors shipping companies have committed to this path on the mid long term, raising new buildings programs for vessels capable of using methanol (Ang, 2022), (A.P. Moller - Maersk, 2022). Considering the changing environment, the evolving regulatory framework, and the sensitive ranges on energy prices, an evaluation under the VIKOR framework, using incomplete weights and consequences in intervals shall provide a representative perspective on the subject. Employing fuzzy logic approach through fuzzy VIKOR or fuzzy TOPSIS methods in future studies could improve the management of qualitative scale criteria, while a modification on the quantitative criteria shall be required. An aspect of the shipping decarbonisation enigma which requires further modelling, is the adjoining of alternative solutions. The flexibility and available options for future retrofitting are a great incentive for the decisions made today. To gradually accommodate different technologies, and more sustainable fuel alternatives in the energy mix with the same, or similar equipment set, the decision made at this early stage is crucial. Researching pathways and selecting alternatives should be assessed in the short, mid, and long term, as the selection today unlocks the future potential on an asset with a lifespan of 20-30 years.

Bibliography

A.P. Moller - Maersk, 2022. *A.P. Moller - Maersk engages in strategic partnerships across the globe to scale green methanol production by 2025,* s.l.: A.P. Moller - Maersk.

American Bureau of Shipping, 2022. *Zero Carbon Outlook,* s.l.: s.n.

Ang, I., 2022. *CMA CGM to save millions by building methanol-fuelled container ships in China,* s.l.: TradeWinds.

Assefa, G. & Frostell, B., 2006. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. *Technology in Society,* pp. 63-78.

Balezentis, T., Streimikiene, D. & Siksnelyte-Butkiene, I., 2021. Energy storage selection for sustainable energy development: The multi-criteria utility analysis based on the ideal solutions and integer geometric programming for coordination degree. *Environmental Impact Assessment Review.*

Bazzazi, A. A., Osanloo, M. & Karimi, B., 2011. Deriving preference order of open pit mines equipment through MADM methods: Application of modified VIKOR method. *Expert Systems with Applications,* Volume 38, pp. 2550-2556.

Bengtsson, S., Fridell, E. & Andersson, K., 2012. Environmental assessment of two pathways towards the use of biofuels in shipping. *Energy Policy,* pp. 451-463.

Bilgili, L., 2021. Comparative assessment of alternative marine fuels in life cycle perspective. *Renewable and Sustainable Energy Reviews.*

Chang, C.-L., 2010. A modified VIKOR method for multiple criteria analysis. *Environmental Monitoring and Assessment* , Volume 168, pp. 339-344.

Chen, T.-Y. & Li, C.-H., 2010. Determining objective weights with intuitionistic fuzzy entropy measures: A comparative analysis. *Information Sciences*, pp. 4207-4222.

COP26, 2021. *Declaration on Zero Emission Shipping by 2050,* Glasgow: UN Climate Change Conference.

Deniz, C. & Zincir, B., 2015. Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production,* pp. 438-449.

Directive (EU) 2018/2001, 2018. On the promotion of the use of energy from renewable sources. *Regulation of the European Parliament and of council.*

DNV GL , 2019. *Alternative marine fuels study,* s.l.: s.n.

Elsevier Analytical Services, 2021. *Pathways to Net Zero: The Impact of Clean Energy Research,* s.l.: Elsevier.

European Commission, 2021. *Climate Action.* [Online]
Available at: https://climate.ec.europa.eu/eu-action/european-green-deal/2030-climate-target-plan_en
[Accessed 4 10 2022].

European Commission, 2021. On the use of renewable and low-carbon fuels in maritime transport and amending. *Regulation of the European Parliament and of the council.*

European Commission, 2021. *Proposal for a directive of the european parliament and of the council amending Directive 2003/87/EC,* Brussels: European Commission.

Flamos, A., Doukas, H. & Psarras, J., 2009. Data validation platform for the sophisticated monitoring and communication of the energy technology sector. *Renewable Energy,* pp. 931-935.

Gilbert, P. et al., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. *Cleaner Production*, pp. 855-866.

Gurjar, B., Butler, T., Lawrence, M. & Lelieveld, J., 2007. Evaluation of emissions and air quality in megacities. *Atmosperic environment,* pp. 1593-1606.

Hansson, J., Mansson, S., Brynolf, S. & Grahn, M., 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass and Bioenergy,* pp. 159-173.

Hsieh, C.-w. C. & Felby, C., 2017. *Biofuels for the marine shipping sector,* s.l.: IEA bioenergy.

Hwang, C. -L. & Yoon, K., 1981. Multiple Attribute Decision Making: Methods and Applications. In: *Multiple Attribute Decision Making.* Berlin, Heidelberg: Springer.

IEA, 2021. *International Shipping,* Paris : https://www.iea.org/reports/international-shipping.

Kaya, T. & Kahraman, C., 2010. Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul. *Energy*, 35(6), pp. 2517-2527.

Kim, J. H. & Ahn, B. S., 2019. Extended VIKOR method using incomplete criteria weights. *Expert Systems With Applications,* pp. 124-132.

Korberg, A., Brynolf, S., M., G. & I.R., S., 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews.*

Koutsandreas, D. et al., 2022. Risks and mitigation strategies in energy efficiency financing: A systematic literature review. *Energy reports*, pp. 1789-1802.

Liu, P. & Wu, X., 2012. A competency evaluation method of human resources managers based on multi-granularity linguistic variables and VIKOR method. *Technological and Economic Development of Economy,* 18(4), pp. 696-710.

Maersk Mc-Kinney Moller Center for zero carbon shipping, 2021. *Maersk Mc-Kinney Moller Center for zero carbon shipping.* [Online]
Available at: https://www.zerocarbonshipping.com/fuel-pathways
[Accessed 14 07 2022].

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022. *Determining the impact and role of onboard vessel emission reduction,* s.l.: s.n.

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022. *Documentation and assumptions for NavigaTE 1.0,* s.l.: s.n.

MAN Energy Solutions, 2020. *MAN B&W two-stroke engine operating on ammonia,* s.l.: s.n.

MAN Energy Solutions, 2021. *Hydrogen in shipping,* s.l.: s.n.

Maritime Knowledge Centre, T. a. T. D., 2020. *Final Report: Assessment of alternative fuels for seagoing vessels using Heavy Fuel Oil* , s.l.: s.n.

Martin, E. P., 2022. *Race for trained seafarers is on — as dual-fuel orderbook grows,* s.l.: TradeWinds.

MEPC.308(73), 2018. *2018 GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY DESIGN INDEX (EEDI) FOR NEW SHIPS,* s.l.: International Maritime Organisation .

MEPC.328(76), 2021. *Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships,1973, as modified by the protocol of 1978 relating thereto 2021Revised MARPOL Annex VI,* s.l.: IMO.

Nikas, A. et al., 2020. Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe. *Energy.*

Opricovic, S., 1998. Multicriteria optimization of civil engineering systems. *Faculty of civil engineering.*

Opricovic, S., 2011. Fuzzy VIKOR with an application to water resources planning. *Expert Systems with Applications,* 38(10), pp. 12983-12990.

Opricovic, S. & Tzeng, G.-H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research,* 156(2), pp. 445-455.

Opricovic, S. & Tzeng, G.-H., 2007. Extended VIKOR method in comparison with outranking methods. *European Journal of Operational Research,* 178(2), pp. 514-529.

Psaraftis, H. N., 2019. *Sustainable Shipping: A cross-disciplinary view.* s.l.:Springer.

Ren, J. & Liang, H., 2017. Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision making approach. *Transportation Research Part D,* pp. 12-29.

Ren, J. & Lutzen, M., 2015. Fuzzy multi-criteria decision-making method for technology selection for emissions reduction from shipping under uncertainties. *Transportation Research Part D,* pp. 43-60.

Ren, J. & Lutzen, M., 2017. Selection of sustainable alternative energy source for shipping: Multicriteria decision making under incomplete information. *Renewable and Sustainable Energy Reviews,* pp. 1003-1019.

Rodríguez, C. G., Lamas, M. I., Rodríguez, J. d. D. & Abbas, A., 2022. Possibilities of Ammonia as Both Fuel and NOx Reductant in Marine Engines: A Numerical Study. *Journal of Marine Science and Engineering.*

Ruojue, L. et al., 2021. Multi-criteria sustainability assessment and decision-making framework for hydrogen pathways prioritization: An extended ELECTRE method under hybrid information. *International Journal of Hydrogen Energy,* pp. 3430-3445.

Sahabuddin, M. & Khan, I., 2021. Multi-criteria decision analysis methods for energy sector's sustainability assessment: Robustness analysis through criteria weight change. *Sustainable Energy Technologies and Assessments.*

Saraswat, S. & Digalwar, A. K., 2021. Evaluation of energy alternatives for sustainable development of energy sector in India: An integrated Shannon's entropy fuzzy multicriteria decision approach. *Renewable Energy,* pp. 58-74.

Sayadi, M. K., Heydari, M. & Shahanaghi, K., 2009. Extension of VIKOR method for decision making problem with interval numbers. *Applied Mathematical Modelling,* 33(5), pp. 2257-2262.

Spoof-Tuomi, K. & Niemi, S., 2020. Environmental and Economic Evaluation of Fuel Choices for Short Sea Shipping. *Clean Technologies*, pp. 34-52.

The European Association for Storage of Energy, 2022. *Energy storage - Technologies.* [Online]
Available at: https://ease-storage.eu/energy-storage/technologies/

United Nations Climate Action, 2021. *United Nation Climate Change.* [Online]
Available at: https://www.un.org/en/climatechange/cop26
[Accessed 1 10 2022].

United Nations Climate Change, 2015. *The Paris Agreement.* [Online]
Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[Accessed 1 10 2022].

van der Maas, T., 2020. *Assessment and comparison of alternative marine fuels towards the decarbonisation of port of Amsterdam,* s.l.: s.n.

Xing, H., Stuart, C., Spence, S. & Chen, H., 2021. Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production.*

Xu, X., 2004. A note on the subjective and objective integrated approach to determine attribute weights. *European Journal of Operational Research*, 156(2), pp. 530-532.
