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Shipping fuel pathways in a changing climate: A prospective foresight study for 2050

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ABSTRACT

This study examines fuel use and environmental impact of shipping industry on Baltic Sea. It focuses on assessing the effects of environmental regulations and proposing decarbonisation scenarios while regulating the SOx and NOx emissions. The abatement measures and alternative fuels as replacements for high-sulphur and carbon-intensive fuels (HFO) are evaluated through technology availability, maturity, fuel price, energy mix and regulation. In the short term, HFO with scrubbers is considered cost-effective, but alternate fuels are expected to replace it with tighter regulations. Liquefied natural gas (LNG), which has zero SOx emission and competitive price range of 230–955 euro per ton, can only be considered as transitional fuel due to methane slip issues limiting its contribution to decarbonisation. For the long term, methanol, hydrogen, and ammonia are potential solutions for achieving SOx free emissions and meeting decarbonisation targets with best possible share of 30 %, 35 % and 35 % respectively. In case of greener fuels, price range varies from 350 to 995 euro/t for ammonia, 100–600 euro/t for hydrogen, and 300–700 euro/t for methanol in 2050, with minimum capex value of 200–400 euro/kW for methanol. Scaling up methanol and advancing hydrogen and ammonia technologies require significant industry and regulatory efforts to achieve the 2050 emission reduction targets of net zero emissions.

1. Introduction

The shipping industry is currently going through a transitional phase with a focus on green shipping. Mitigation efforts are primarily driven through policy and regulatory mechanisms developed by international and regional bodies [1]. Over the last few decades, the International Maritime Organization (IMO) has facilitated stricter regulations through the International Convention on the Prevention of Marine Pollution from Ships (MARPOL), which targets pollution from the shipping industry that damages the atmosphere and marine ecosystem.

Recognising the threat posed by greenhouse gas (GHG) emissions, the IMO introduced the Energy Efficiency Design Index (EEDI) in 2011 to incentivise improved energy efficiency in newly built vessels. Additionally, the Ship Energy Efficiency Management Plan (SEEMP) was implemented to monitor energy efficiency [2]. However, EEDI is considered a soft measure since it only applies to newly built vessels, and SEEMP lacks CO2 reduction targets.

It was only in 2018 that the IMO's Marine Environment Protection Committee (MEPC) adopted a strategy for the reduction of GHG emissions. This strategy introduces measures at various scales with the ultimate goal of decarbonizing the shipping sector by 2100. IMO also set the target to reduce CO_2 emissions by 50 % by 2050 [3]. It established three guiding principles to reduce the carbon intensity of the ships i) implementing EEDI, ii) reducing CO_2 from international shipping by 40 % by 2030 and 70 % by 2050 compared to 2008 (IMO, 2018), iii) reducing overall annual GHG emission by at least 50 % compared to 2008. Later,

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two regulatory frameworks i.e. Energy efficiency existing ship index (EEXI) and Carbon intensity indicator (CII) were introduced. The EEXI sets design-based standards for energy efficiency in existing ships, while the CII monitors operational carbon emissions relative to cargo and distance [4]. Recent revision of the targets in MEPC 80, July 2023, to 70 % by 2040 and net-zero by 2050, have brought the stringent implementation of EEXI and CII in focus as a short-term measure [4]. However, the absence of clear guidelines on pathways and compliance methods leaves ample space for strategic manoeuvring among the stakeholders in the shipping industry [5].

Another important intervention was the implementation of the Emission Control Area (ECA) in 2005, aimed at reducing shipping emissions of nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter (PM). The primary source of SOx emissions is the use of heavy fuel oils (HFO) with high sulphur content in ships. To address this, the United Nations agency implemented two Sulphur caps in 2015 and 2020 to reduce oxide gas emissions from the shipping industry [6]. These regulations require SOx and PM emissions to be below 0.5 % mass per mass and 0.1 % mass per mass, respectively, outside and inside the Emission Control Areas (ECAs) (details provided in Table 1) [7].

Until recently, shipping companies considered switching to liquefied natural gas (LNG) [8] or installing exhaust gas cleaning systems, known as scrubbers [9], as the most viable solutions to meet these regulations. However, concerns raised in recent years have cast doubt on the development of these technologies. Open-loop (OL) scrubbers, the cheapest scrubber technology, release chemicals into seawater, which may have ecological implications [9–12]. On the other hand, LNG releases unburned methane, known as "methane slip," which contributes to the global warming crisis [13,14]. As a result, countries are progressively banning OL scrubbers, and international organizations have lost confidence in LNG as a long-term solution [15,16]. Sales of scrubbers have decreased, and a similar trend is expected for LNG [8].

HFO and distillate forms are still in extensive use by large ships, as these are cost-efficient and provide high energy efficiency from well to propeller (WTP) perspective [17] However, the consistent push for carbon neutrality and net-zero emissions opens the pathways for greener alternative fuels, (Tables 2 and 3). The transport industry is gradually shifting focus beyond low-sulphur fuels such as marine diesel and LNG to methanol and other biofuels. Other solutions, such as ammonia or hydrogen-fuelled ships, are still embryonic but are the most promising alternatives before methanol or biofuels [18,19]. Until these technologies are operational, the ships to which emission regulations apply are left with the option of using expensive low sulphur fuel oil (LSFO) and derivatives, LNG and heavy HFO, in conjunction with the scrubbers. In regions where water exchange is limited, such as the Baltic Sea, the condition worsens because it may not be possible to achieve the necessary level of dilution to maintain the natural chemistry of the seawater [7,20].

Given these uncertainties, the shipping companies' strategies to comply with emission regulations are unclear. In such situations, the detailed assessment and impact of potential solutions on the environment are often compromised. As we are already in the midst of climate change crises and struggling to achieve the net zero CO_2 emissions goal, any negligence at the planning stage could pose a severe long-term threat to our fragile ecosystem. This points to the need to evaluate different scenarios which can provide an optimal solution [22]. Studies, like [23], have examined the adoption potential of specific fuels by comparing their life-cycle benefits. However, life-cycle assessments often overlook broader factors such as technological progress, availability, and regulatory hurdles. A SWOT analysis, as proposed by [24,25] offers a more comprehensive approach but lacks fuel mix scenario. Unlike previous studies, this study presents a forward-looking approach to identify optimal fuel mix scenarios for achieving net-zero carbon emissions while regulating shipping pollutants like SOx and NOx. By integrating evolving regulations, technological advancements, and both global and regional factors, it provides a comprehensive analysis of fuel adoption in the maritime sector. A key consideration is the inclusion of stakeholder feedback, offering real-world insights into the expected market penetration of relevant technologies by 2050. It further contributes by evaluating the practical implications of fuel adoption, exploring underexamined environmental impacts of current solutions such as LNG and scrubbers. The value lies in providing insights for policymakers and industry, blending technological feasibility with regulatory compliance, while stressing the risks of delaying sustainable fuel adoption and offering a roadmap to decarbonisation.

Table 1
Current emission control areas [7].

Region	Applied for	Adopted	Enforced
Baltic Sea	1995 (SECA) 2016 (ECA)	1997 (SECA) 2017 (ECA)	2006: 1.5 % max S 2010: 1 % max S 2015: 0.1 % max S 2021: Tier III NOx
North Sea	2000 (SECA) 2016 (ECA)	2005 (SECA) 2017 (ECA)	2007: 1.5 % max S 2010: 1 % max S 2015: 0.1 % max S 2021: Tier III NOx
North America (United States & Canada except the Arctic)	2009 (ECA)	2010 (ECA)	2012: 1 % S max 2015: 0.1 % S max 2016: Tier III NOx
United States Caribbean Sea (Puerto Rico & U.S. Virgin Islands)	2010 (ECA)	2011 (ECA)	2014: 1 % S max 2015: 0.1 % S max 2016: Tier III NOx

2. Methodology

Several methodologies have been used to evaluate the pathways, each with distinct advantages and limitations. Life Cycle Assessment (LCA) is a widely used method that offers a comprehensive evaluation of the environmental impact of fuel options, assessing emissions across the entire fuel lifecycle from extraction to combustion. However, LCA can be data-intensive and often overlooks economic factors, which limits its applicability in real-world decision-making [26]. In contrast, Techno-Economic Analysis integrates both technical and economic assessments to evaluate the feasibility of fuel pathways. While it balances technical and economic factors, its accuracy is often hampered by uncertainties such as fluctuating fuel prices and evolving regulations [27]. Other methodologies like Policy and Regulatory Framework Analysis examines how international and regional regulations influence fuel adoption, but it tends to lack the technical and economic depth offered by other methodologies [28,29]. Multi-Criteria Decision Analysis (MCDA), and Scenario Analysis, offer additional insights. MCDA allows for the evaluation of multiple fuel options against diverse criteria, making it highly flexible for integrating various stakeholder preferences, but it may introduce bias through subjective weighting [28]. Scenario analysis provides a forward-looking approach to fuel assessment, offering insights into how different fuel options may evolve under various future conditions. Although these models are highly rigorous, their effectiveness is often constrained by the quality and availability of input data. Each of these methodologies contributes uniquely to the study of shipping fuel pathways, offering complementary perspectives while

Table 2
GHG emission factors and sulphur content in different fuels types [15,21].

	LNG High	LNG low	HFO	MDO	LSHFO	H_2	NH_3	Methanol
Sulphur content (%)	na	na	3.5	0.1–0.5	0.5	na	na	na
Up- and midstream CO_2eq	24.67	8	10.37	10.09	10.37	3.9	12.36	2
Up- and midstream CO_2	8.73	2.91	8.4	7.98	8.4	3.67	12.23	2
Downstream CO_2eq	73.87	59.69	78	79.5	78	0	0	69
Up- and midstream CO_2	50	50	76.8	75.3	76.8	0	0	69

*All numbers in gCO2eqMJ

Table 3
Categories representing the uncertainties and impact of the factor levels.

	Low uncertainty	High uncertainty
Low impact	Context shapers	Potential jokers
High impact	Significant trends	Pivotal uncertainties

presenting challenges in their implementation.

This section outlines the methodology used for present scenario analysis, aiming to explore possible, probable, and desirable future developments. The approach focuses on identifying key factors that will shape the future, combining techniques such as goal-setting, communication, and decision-making, which can be quantitative, qualitative, or both [30] [31]. Overall, the steps shown in Fig. 1 are used in the present study.

2.1. Scenario building

2.1.1. Identification of key factors

This step aims to identify key factors, which can be "variables, parameters, trends, developments, and events, which receive central attention during the further course of the scenario process" [30] Key factors—variables, trends, and events crucial to the scenario process—were identified through a literature review and expert consultations. Experts evaluated 25 factors, categorizing them and providing feedback to refine them. The relationships between factors were analysed using an influence matrix, where factors were mutually compared to assess the degree of influence [30] (Fig. 2).

2.1.2. Analysis of key factors

We then defined potential levels for each key factor and conducted a risk analysis to evaluate their impact and unpredictability. A consistency analysis followed, where we assessed the logical compatibility of these levels, discarding inconsistent combinations. The remaining factors were used to form the basis for potential scenarios.

2.1.3. Scenario generation

Some scenarios are generated from the consistent, high-impact factors. Each scenario is evaluated based on plausibility, differentiation, consistency, decision-making utility, and its ability to challenge conventional thinking. They are then gathered and developed into narratives [31] (Figs. 3 and 4).

2.1.4. Scenario transfer

Stakeholders, both internal and external, were consulted to evaluate the likelihood and implications of each scenario. Before assessing economic and environmental impacts, we gathered feedback on the expected market penetration of relevant technologies by 2050, helping to refine the scenarios further.

3. Key factors

3.1. Identified key factors

Based on the literature review and consultation with the experts, 25 factors are identified and further classified under five categories, i.e. *Energy mix, Fuel technology availability, Fuel/Technology maturity (including investment cost), Fuel price and regulation/incentive*. These factors are then studied and validated in terms of their global, international, or regional perspective.

The validated factors are then defined using the influence matrix, which assesses the degree of networked interrelationships. Active/Impulsive i.e. influences problem field more than it is influenced, and Critical/Dynamic factors i.e. strong influence, but it is interconnected with other factors, are the key factors that will most significantly influence the scenarios. The other factors should not be systematically discarded but should not be considered drivers of the scenarios. The definition of factors amongst the active, passive, critical and buffering categories was (quasi-)unanimous for 17 out of the 25 factors. Our assessment did not reach a consensus for the remaining factors, with equality in some categories (Table 4). For these, we individually and arbitrarily assessed the factors based on the definition of each category (Table 4).

In the end, 4 factors are considered active (i.e., world shipping energy consumption, HFO fuel price, hydrogen fuel price and international regulation), and 5 are critical (i.e., global fossil energy consumption, Baltic shipping fleet, green energy in the Baltic, regional and national regulation). These represent the 9 key factors of our analysis, i.e., the ones that will be at the basis of the scenario creation.

We generated 3888 potential scenarios by combining key factors, but narrowed it down to 64 scenarios using a consistency matrix (Table 5).

We then qualitatively assessed each factor's level of certainty and impact on the system (Table 6). When applied to the 64 potential scenarios, we reduce this set to 16 potential scenarios by selecting the scenarios gathering the most *significant trends* and *pivotal uncertainties* (Fig. 10).

3.2. Analysis of key factors

The current subsection describes the projection of potentials values (levels) for the key factors of each of the five categories.

3.2.1. Energy mix

3.2.1.1. Global Fossil Energy Consumption. Coal production is expected to reach its peak around 2050.[32]. The reserve-to-production ratio for oil, gas, and coal stands at approximately 49.9, 49.8, and 132 years respectively. Short-term projections indicate a decline in oil production while natural gas and other energy sources are anticipated to increase to compensate for the decline[33]. Global environmental agreements like the Paris Agreement and the IMO's sulphur cap are driving the shift towards alternative fuels due to the adverse environmental impact of fossil fuels. However, global energy consumption continues to rise steadily.

According to BP's business-as-usual scenario (level A), which assumes similar reserve-to-production ratios, the reduction in natural gas production is avoided by using unconventional natural gas (Fig. 5)[34]. However, in level B, a significant reduction in both oil and gas production is expected due to low reserves and stricter international regulations (Fig. 5). Study did not include coal in the analysis, despite its

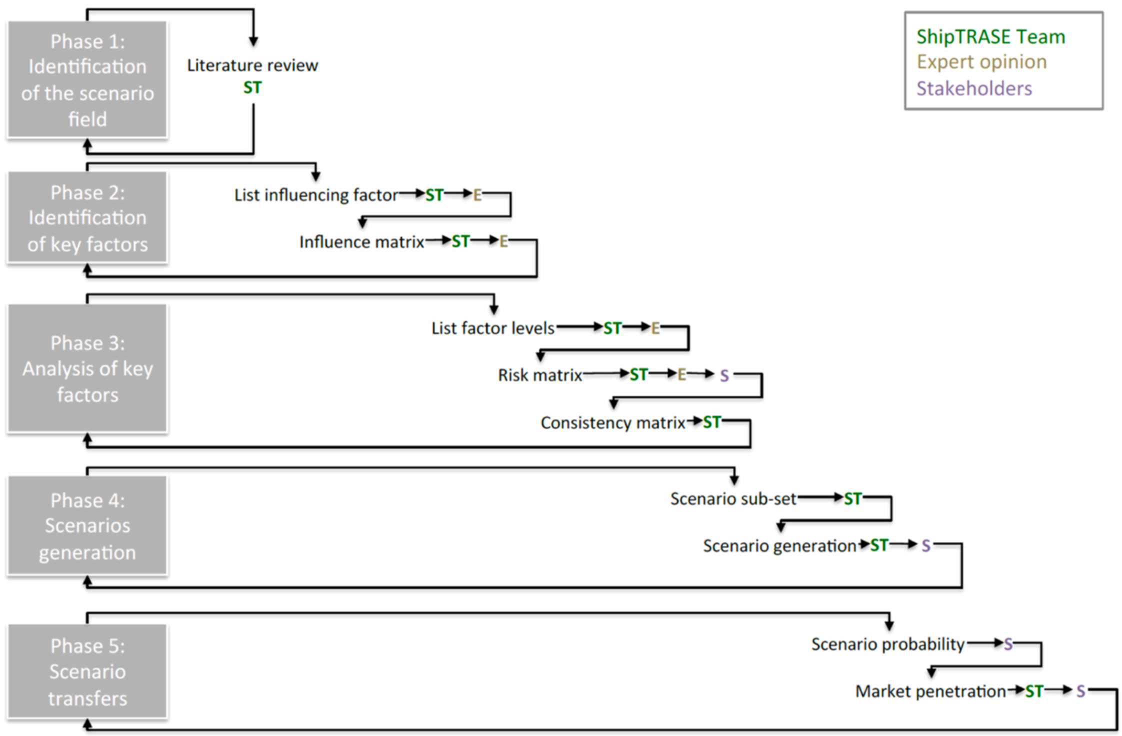

Fig. 1. The scenario-building process is in five phases and the workflow.

Impact Of / On	Factor A	Factor B	Factor C	Factor D	Active Sum (AS)
Factor A		3	3	1	7
Factor B	0		3	2	5
Factor C	1	1		2	4
Factor D	3	3	1		7
Passive Sum (PS)	4	7	7	5	

Fig. 2. Conceptual Example of an Influence matrix [30].

How do lines and columns (i.e. "a" and "b" characteristics) interrelate?		Factor A		Factor B		Factor C		Factor D	
		Value Aa)	Value Ab)	Value Ba)	Value Bb)	Value Ca)	Value Cb)	Value Da)	Value Db)
Factor A	Value Aa)								
	Value Ab)								
Factor B	Value Ba)	2	4						
	Value Bb)	5	2						
Factor C	Value Ca)	5	2	2	5				
	Value Cb)	3	4	5	2				
Factor D	Value Da)	4	3	1	3	5	2		
	Value Db)	3	4	3	4	4	2		

Fig. 3. Consistency matrix (conceptual example)[30].

importance for methanol production, since the reserve-to-production ratio was beyond the scope of the study. The projections of the oil production assumed to follow a 0.0537 % and a −1.9067 % (decrease) annual growth rate for the level A (BAU) and level B (best case), respectively[35]. The annual growth rates for the gas production projections were 0.8719 % and −0.3605 % for level A and level B,

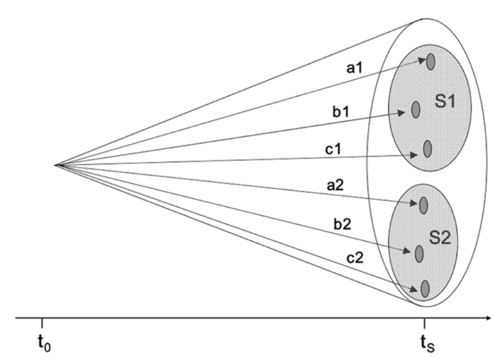

Fig. 4. Selection of relevant scenarios amongst the possible ones. For instance, a1, b1 and c1 describe a similar variation of a potential future S1. At this step, we should select only one option amongst a1, b1 and c1. Modified from[30].

respectively [34].

3.2.1.2. Green energy in the Baltic Sea region. As presented in Fig. 6, In level A, the share of renewable energy in the BSR portfolio is expected to increase by 1.43–2.45 % annually, according to a linear regression analysis of Eurostat data from 2004 to 2019 (R2 =0.99). In level B, the expected growth rate of renewable energy in the BSR portfolio is 3 % per year, based on the IEA and Eurostat average growth rate [36–38]. Level C involves a higher commitment from stakeholders, in line with the latest amendment of the Renewable Energy Directive [36,37,39]. Consequently, the annual growth rate of renewable energy would experience a 20 % increase (resulting in 3.6 % growth per year) in the first half of the period (2020–2035) and a 3.35 % annual growth on the rest of the period to 2050. Based on this assumption, it becomes possible to achieve a 100 % renewable energy share by 2050 under level C.

3.2.2. Fuel and technology availability

In the literature, the availability of relevant infrastructure is defined by the compatibility of the alternative marine fuel to existing

Table 4
Summary of the influence matrixes (normalised; A) and final assessment, partly based on the category definition for factors where consensus was not reached (in grey; B).

	A				B			
	ACTIVE	PASSIVE	CRITICAL	BUFFERING	ACTIVE	PASSIVE	CRITICAL	BUFFERING
ENERGY MIX								
World Ship. Energy Consumption	=	0	=	0	1	0	0	0
Global Fossil Energy Consumption	0	0	1	0	0	0	1	0
Baltic Shipping Fleet	0	0	1	0	0	0	1	0
Green energy in the Baltic	0	0	1	0	0	0	1	0
FUEL/TECH. AVAILABLE.								
LNG availability at port	0	1	0	0	0	1	0	0
Ammonia availability at port	0	1	0	0	0	1	0	0
Hydrogen availability at port	=	=	0	=	0	1	0	0
Methanol availability at port	0	1	0	0	0	1	0	0
Scrubber facilities available at port	0	0	0	1	0	0	0	1
FUEL/TECH. MATURITY (M-TRL)								
LNG readiness	=	=	0	=	0	1	0	0
Ammonia readiness	=	=	=	0	0	1	0	0
Hydrogen readiness	0	1	0	0	0	1	0	0
Methanol readiness	0	=	=	=	0	1	0	0
Scrubber readiness	0	0	0	1	0	0	0	1
FUEL PRICE								
HFO fuel price	1	0	0	0	1	0	0	0
LNG fuel price	=	=	0	=	0	1	0	0
Ammonia fuel price	0	1	0	0	0	1	0	0
Hydrogen fuel price	1	0	0	0	1	0	0	0
Methanol fuel price	0	0	0	1	0	0	0	1
REGULATION/ INCENTIVE								
International Regulation	1	0	0	0	1	0	0	0
Regional Regulation	0	0	1	0	0	0	1	0
National Regulation	0	0	1	0	0	0	1	0
International Incentive	=	=	0	=	0	1	0	0
Regional Incentive	=	=	0	=	0	1	0	0
National Incentive	0	1	0	0	0	1	0	0

infrastructure, adaptability to existing ships, and the current amount of storage and bunkering capability[1] [40].The reliability of the supply chain is defined by raw material availability, current fuel production, current use as fuel in the shipping sector, global distribution of supply potential, and political stability in countries with considerable supply potential.

3.2.2.1. LNG availability in the Baltic Sea region. (supply chain, production and storage capacity)

The overall LNG capacity of the Baltic Sea Region to the rest of Europe [41]. Norway and Russia are in the top 10 worldwide producers of LNG, several facilities proposing bunkering to ships already exist in the BSR and several others are planned. By 2026, storage capacity is expected to be 26 % higher than the current capacity [41,42]. Except for Sweden, Estonia and Finland, LNG represents between 14 % and 31 % of the energy mix in the BSR [43]. The future availability of bio-LNG for maritime applications is likely to be limited due to high production costs

[1] Hansson et al., 2019 also included engine technology maturity that we classified in another factor type (i.e., Technology Maturity)

Table 5
Consistency matrix. The cell in red represents the combination of factors with a weak or strong inconsistency (complete or mutual opposition).

		World Shipping Energy Consumption			Global Fossil Energy consumption		Baltic Shipping Fleet			Green energy in the Baltic (% of renewable in energy mix)			HFO fuel price			Hydrogen fuel price			International Regulation (e.g., IMO level)		Regional Regulation (e.g., UE level)		National Regulation (e.g., country level)	
		Slight decrease	Slight increase	Significant increase	Slight decrease	Significant decrease	Slight decrease	Significant increase	(Really) significant increase	Slight increase	Significant increase	(Really) significant increase	Stable	Slight increase	Significant increase	Significant decrease	Stable	Significant increase	Regulation as planned	Stronger regulation than planned	Regulation as planned	Stronger regulation than planned	Regulation as planned	Stronger regulation than planned
World Shipping Energy Consumption	Slight decrease																							
	Slight increase																							
	Significant increase																							
Global Fossil Energy consumption	Slight decrease	4	3	3,33																				
	Significant decrease	4	2,33	1,67																				
Baltic Shipping Fleet	Slight decrease	3	2,33	2,33	3,33	3,67																		
	Significant increase	1,33	3,33	3	1,67	1,67																		
	(Really) significant increase	1,33	3,67	3,67	1,33	1,33																		
Green energy in the Baltic (% of renewable in energy mix)	Slight increase	2	3,33	3	3,33	3	2,33	2,67	2,33															
	Significant increase	2	3,33	3,67	3,67	3,33	2,33	2,67	2,33															
	(Really) significant increase	2	3,33	3,67	4,33	4,33	2,33	2,67	2,33															
HFO fuel price	Stable	2,33	3,33	3,33	2	2	3	3	2,67	2,67	2,67	2,33												
	Slight increase	4	2,33	2	4	4	3	3	3	3,67	3,67	3,67												
	Significant increase	4,67	2	2	4,67	4,33	3	3	3	4,67	4,33	4,33												
Hydrogen fuel price	Significant decrease	2,33	3,67	3,67	4	4	2,67	3,33	3	4,33	4	4,67	3,33	3	2,33									
	Stable	3	3,33	3,33	3,33	3,33	3,33	3	3	3,33	3	2,67	3	3	3									
	Significant increase	3	3	2,67	3	3	3,33	3	3	2,33	2,33	2	3	3	3									
International Regulation (e.g., IMO	Regulation as planned	3,67	3,33	3	3,67	3,33	3	3	3	3,67	3,67	3,67	3	3	3	3	3	3						
	Stronger regulation than planned	3,67	3	2,67	4,33	4	3,67	2,33	2,33	4,33	4,67	4,33	3	3,67	4	4	3	2						
Regional Regulation (e.g., UE level)	Regulation as planned	3	2,67	2,67	3,33	3,33	3	3	3	3,67	3,67	3,33	3,33	3,33	3	3	3,33	2,67	3	2,333333				
	Stronger regulation than planned	4	2	2	4	4	3,67	2,33	2,33	4,33	4,67	4,33	3,33	3,67	3,67	4,33	3	2	3,333333	4				
National Regulation (e.g., country level)	Regulation as planned	3	3	3	3,33	3,33	3	3	3	3,67	3,67	3	3,33	3,33	3	3	3,33	3	3,333333	2,333333	3,333333	2,333333		
	Stronger regulation than planned	3,33	2,67	2,67	3,67	3,33	3,67	2,33	2,67	4,33	4	4	3,33	3,33	3,33	4	3,33	2,33	3	4,333333	3	4,333333		

Significant decrease	↘ (red)
Slight decrease	↘ (orange)
Stable	=
Slight increase	↗ (light green)
Significant increase	↗ (dark green)
(Really) significant increase	↑

Strong inconsistency (complete opposition).	1
Weak inconsistency (mutual opposition)	2
Neutrality or independence from one another	3
Weak consistency (mutual support)	4
Strong consistency (strong mutual support)	5

or competition with other sectors [21].

Despite the increase of LNG facilities in the BSR in the short term [41], we observe a stagnation of LNG facilities related to shipping (e.g., bunkering) under level A. After a slight increase in LNG's share in the short term, a decrease in the long term will be observed due to low market penetration and the emergence of other alternative fuels (Fig. 7) [15]. Level B shows a small amount of progress for LNG, where the planned facilities are built [41], and the development of LNG facilities follows the current worldwide trend, i.e., 4.7 % [34]. As a result, LNG facilities may provide about 20 % of fuel for BSR shipping in 2050, which is consistent with IMO (2020) estimations (Fig. 7). Under an optimistic scenario of level C, the planned facilities are built, and the development of LNG facilities follows the current BSR trend, i.e., 10.1 % [41] providing significant additional supply. Facilities may provide up to 40 % of fuel for BSR shipping in 2050 (Fig. 7). This increase in LNG availability would most likely not meet IMO regulations on GHG [44].

3.2.2.2. Ammonia availability in the Baltic Sea region. As ammonia-fuelled ships are still at the prototype stage, the availability of this fuel in ports is poor [46]. Once these vessels are available, the supply chain to provide ammonia bunkering in port should rapidly increase. Ammonia plants can be built to supply the demand for shipping, which will take around 3 years of building for each plant. LNG facilities for shipping can be re-used, but the conversion is expensive. However, NG plants can be used to produce ammonia [15].

Level A tends to show poor development despite the presence of several production facilities around Europe, infrastructures required for shipping applications are not built, and the availability of ammonia remains low in the short term (Fig. 8). A ramp-up phase is observed around 2040–2050 when ammonia-fuelled ships could be expected. A moderate scenario is observed under level B. Here, a ramp-up phase, infrastructures for shipping are built, and dedicated ammonia production for shipping starts around 2030. It can provide up to 12.5 % of BSR shipping energy by around 2040 [47] and up to 20 % around 2050 (Fig. 8). Comparatively better growth forms the basis of level C, in which it could be possible that ammonia comprises up to 25 % of BSR shipping energy by around 2040, and up to 35 % around 2050 (Fig. 8). The improvement of shipping infrastructures for ammonia is boosted by world organisations support, e.g., strategy, funding [15,46]and the introduction of green ammonia plants [48].

3.2.2.3. Hydrogen availability in the Baltic Sea region. (supply chain, production and storage capacity)

Hydrogen is a step behind ammonia, as Ammonia outperforms hydrogen in energy density, storage, and production cost due to existing infrastructure [18]. Hydrogen plants are quicker to build, with lower well-to-wheel emissions, though converting LNG infrastructure is expensive. [18]. Liquefied hydrogen is more energy-demanding, and no ships currently use it. [49]. The first synthetic fuel facility was planned in Norway in 2020. [50]. Lithuania, Poland, Russia and Sweden currently produce 5.7 % of hydrogen worldwide[51].

Under level A, investments in this fuel for shipping are limited due to technological constraints, e.g., safety and environmental impact [52] Furthermore, the ramp-up phase only starts in 2040, leading to 4 % of potential shipping energy provided by hydrogen by 2050 (Fig. 9) [46,53,54]. A moderate approach is shown in level B, in which after a ramp-up phase, infrastructures for hydrogen production and shipping-related facilities (e.g., port facility adaptations) would start operational in 2035, leading to 15 % of potential shipping energy provided by hydrogen by 2050 (Fig. 9) [50]. A relatively better opportunity arises in level C, as investments in green hydrogen production would boost global production leading to 35 % of potential shipping energy provided by hydrogen by 2050 (Fig. 9) [50,55].

3.2.2.4. Methanol availability in the Baltic Sea region. (supply chain, production and storage capacity)

Though, methanol production in the BSR grows faster than the world average, i.e. 7 % vs 6 % [17,56], is limited, with only 5 % worldwide production and 0.5 % storage capacity [17]. More broadly, Europe is a major net importer of methanol (IHS Markit, 2017). Although methanol

Table 6
Results of the certainty and impact analysis of the key factors. In green are the answers given by the expert in the previous step.

Factor Code	Key factor	Level	Trend toward 2050	Certainty	Impact	Definition
EM-1	World Shipping Energy Consumption	A	Slight decrease	Low	Low	Potential jokers
		B	Slight increase	High	Low	Context shapers
		C	Significant increase	Low	High	Pivotal uncertainties
EM-2	Global Fossil Energy consumption	A	Slight decrease	Low	Low	Potential jokers
		B	Significant decrease	High	High	Significant trends
EM-3	Baltic Shipping Fleet	A	Slight decrease	Low	Low	Potential jokers
		B	Significant increase	High	High	Significant trends
		C	Significant increase	Low	High	Pivotal uncertainties
EM-4	Green energy in the Baltic	A	Slight increase	Low	Low	Potential jokers
		B	Significant increase	High	High	Significant trends
		C	Significant increase	Low	High	Pivotal uncertainties
FP-1	HFO fuel price	A	Stable	Low	High	Pivotal uncertainties
		B	Slight increase	High	High	Significant trends
		C	Significant increase	High	High	Significant trends
FP-4	Hydrogen fuel price	A	Significant decrease	High	High	Significant trends
		B	Stable	High	Low	Context shapers
		C	Significant increase	Low	High	Pivotal uncertainties
RI-1	International regulation (e.g., IMO level)	A	Regulation as planned	High	High	Significant trends
		B	Stronger regulation than planned	Low	High	Pivotal uncertainties
RI-2	Regional regulation (e.g., UE level)	A	Regulation as planned	High	High	Significant trends
		B	Stronger regulation than planned	Low	High	Pivotal uncertainties
RI-3	National Regulation (e.g., country level)	A	Regulation as planned	High	High	Significant trends
		B	Stronger regulation than planned	Low	High	Pivotal uncertainties

is well-suited for existing infrastructures and ships due to its good adaptability and lower investment costs compared to LNG, hydrogen, or ammonia [57], it is not a preferred solution for shipping. This is because marine gas oil (MGO) is significantly cheaper and the likelihood of achieving GHG reduction targets is relatively low with methanol [44, 58]. Methanol production through fossil feedstocks has a higher life cycle CO_2 emission than conventional fuels [44,59]. However, the development of renewable methanol (i.e., biomass- or e- based) solves this issue, but the operational and capital costs are comparatively high. Several BSR countries are building bio- and e-methanol facilities, such as Sweden, Norway, Germany, Belgium and Denmark [56]. In a recent development, Maersk announced the order of 19 green methanol vessels to help achieve their net-zero emission target by 2040, which could be a significant development[60]. Despite the good potential, the methanol penetration of the market is delayed because infrastructures to produce and propose renewable methanol (i.e., the only one reaching GHG

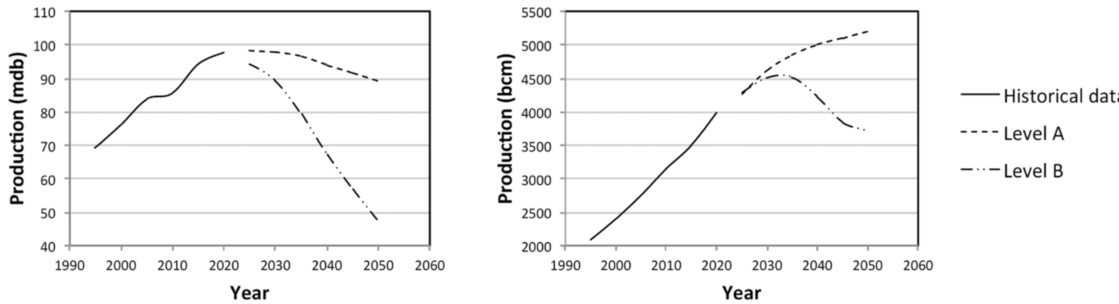

Fig. 5. Projections of oil (left) and natural gas (right). Level A is BAU and B is best-case scenario. Data source: [33,34].

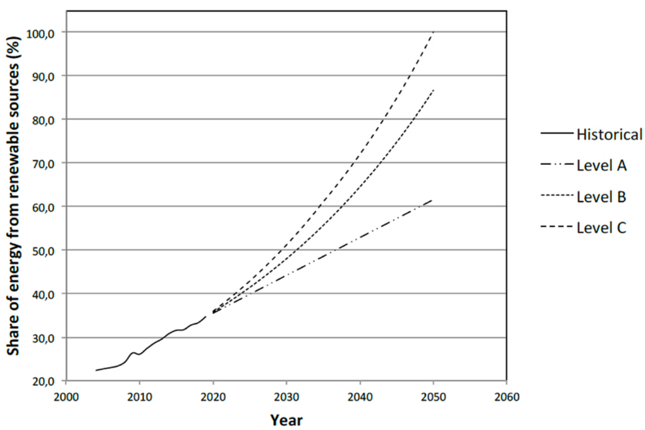

Fig. 6. Projections of the share of renewable energy based on levels. Level A is the BAU scenario, level B is the intermediate scenario, and level C is the best-case scenario. Data source:[38] [37]IEA, 2019; Eurostat, 2021).

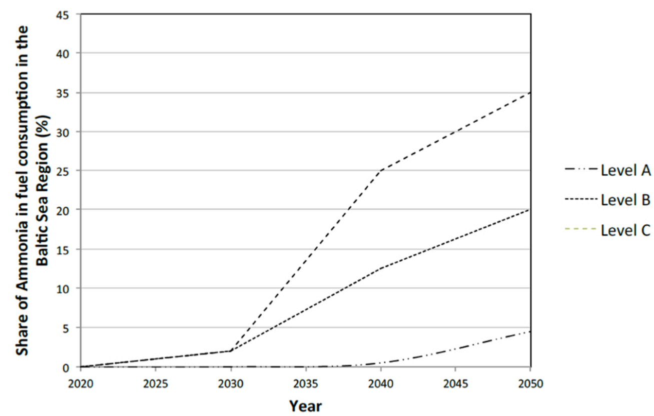

Fig. 8. Projections of the potential share of ammonia in fuel consumption in the Baltic Sea Region. Level A is the poor scenario, level B is the moderate scenario, and level C is the fairly good scenario [15,46,47].

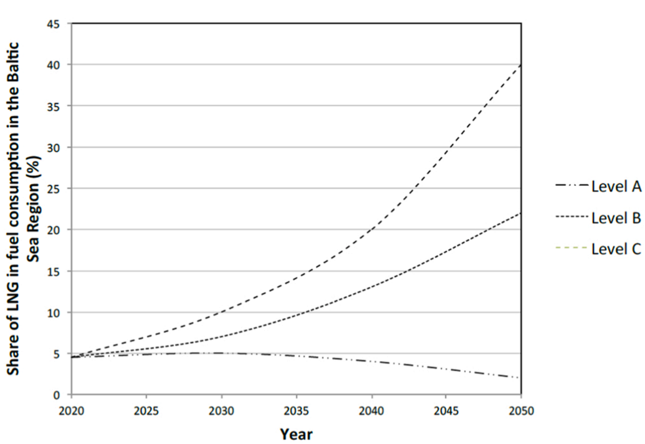

Fig. 7. Projections of the potential share of LNG in fuel consumption in the Baltic Sea Region. Level A is the moderate scenario, level B is the fairly good scenario, and level C is the good scenario. Data source:[15,41,45].

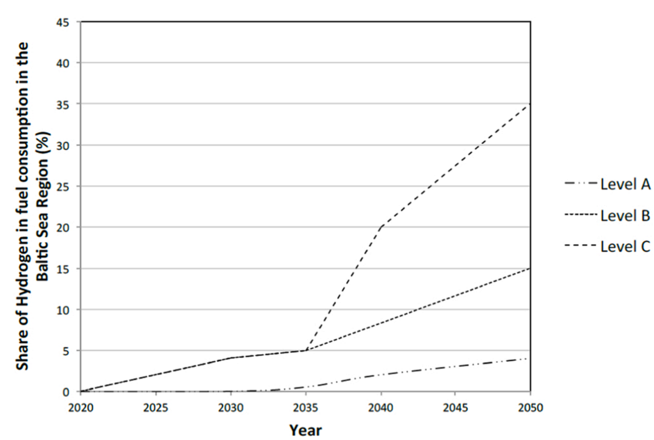

Fig. 9. Projections of the potential share of hydrogen in fuel consumption in the Baltic Sea Region. Level A is the poor scenario, level B is the moderate scenario, and level C is the fairly good scenario [18,50,52–55].

targets) are not available yet.

Poor prospects of methanol in level A is due to the slow development of infrastructure for renewable methanol, while alternative fuels other than methanol are penetrating the market. By 2050, only a small proportion of ships (0.8 %) utilize this fuel (Fig. 10) [17,46,61]. However, under an improved scenario known as level B, an investment in methanol infrastructure leads to a higher adoption rate. Nonetheless, methanol continues to represent a relatively small percentage of the shipping energy mix, amounting to 6 % by 2050 (Fig. 10) [62]. Additionally, bio and e-methanol production remain stagnant, prompting shipping companies to explore alternative eco-friendly fuels. It should be noted that reaching 6 % of methanol in the shipping fuel mix would require that 28 % of the current BSR methanol production capacity be allocated to shipping (or that more than 2 million tons methanol should be produced for shipping [17]. Considering Level C as an optimistic scenario, methanol share in the fuel mix increases with production but reaches a plateau between 2030 and 2040 [63]. This plateau corresponds to the ramp-up phase of bio- and e-methanol production. The significant increase after 2040 toward 30 % of the methanol in 2050 in the shipping energy mix is linked to the high potential in the renewable feedstock in the BSR (Fig. 10). Apart from Russia, biomass represents between 7 % and 32 % of the BSR country energy mixes [43]. The BSR forest coverage

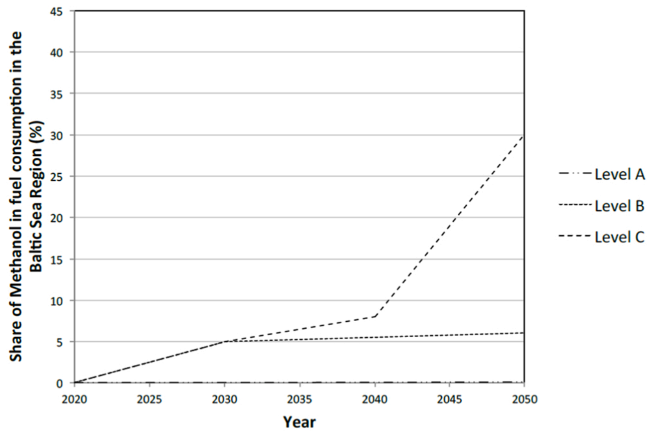

Fig. 10. Projections of the potential share of methanol in fuel consumption in the Baltic Sea Region. Level A is the poor scenario, level B is the moderate scenario, and level C is the fairly good scenario. Data source:[17,61–63,65].

offers opportunities for developing bioenergy [64]. Country strategies demonstrate this potential, such as Estonia's goal to reach 80 % of heat and 50 % of electricity from renewables by 2030 [64]. Sweden, Latvia and Estonia are among the top 10 pellet producers worldwide [64].

3.2.2.5. Availability of scrubber facilities in the Baltic Sea region. (scrubber waste facilities in the port)

Most major BSR commercial ports have installed closed-loop scrubber waste facilities. In more detail, 63.3 % of the 139 major BSR ports (i.e., 90 % of BSR port calls) are equipped with scrubber waste facilities (IHS Markit data, 2020). It should be noted that "waste facilities" processing facilities; ships can get rid of scrubber water in 63.3 % of major ports, but ports send this water to be processed externally.

National and regional regulations have restricted open-loop scrubber technology for environmental reasons, which results in decrease in level A [66–68]. The operational and capital costs of alternative fuels are lower than those of closed- or hybrid-loop scrubbers. As a result, the proportion of ships equipped with scrubbers is expected to decrease over time.[8]. Ports will progressively dismantle the scrubber waste facilities, leading to 50 % of major ports being equipped in 2050 (Fig. 11). In level B, although more expensive than open-loop scrubbers, closed-loop or hybrid-loop scrubbers remain cheaper than alternative fuels. The high level of scrubber waste equipment of BSR ports remains stable at 73 % of major ports equipped in 2050 (Fig. 11). Owing to the worst possibilities

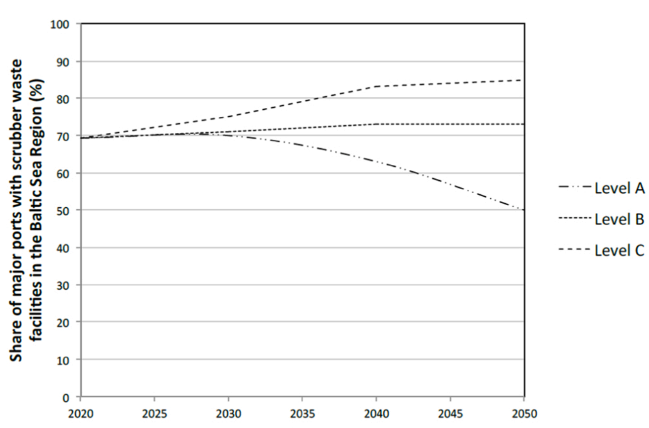

Fig. 11. Projections of the potential share of major ports equipped with scrubber waste facilities in the Baltic Sea Region. Level A shows a sharp decline, level B is the stable, and level C is increased growth scenario. IHS Markit data, 2020;[6,8].

for alternative fuels growth, the technology sees an increase in level C. Alternative fuels that face unexpected environmental and logistic setbacks, such as methane slips in LNG ships [69], provide an unwanted push to closed- or hybrid-loop scrubbers. In addition, HFO fuel price remains lower than other fuels, which facilitates the scrubber waste facilities to rise to 85 % at major ports by 2050 (Fig. 11). This scenario would probably mean that we failed to reach GHG targets.

3.2.3. Fuel and technology maturity

3.2.3.1. Modified technology readiness level (M-TRL). The Modified Technology Readiness Level (M-TRL) is a nine-level scale[2] that describes increasing levels of technical maturity based on demonstrations of capabilities and market penetration. The M-TRL is linked not only to technology maturity but also to regulation and market maturity [70]. In other words, the more a technology matures, the more regulations adapt, and the more the technology penetrates the market. We choose to integrate the market penetration in our M-TRL as the definition of the levels varies depending on the authors, i.e., some technologies are not at the same level for various authors [70–73]. We, therefore, performed a literature review to assess the status of the technology, based on, for instance, whether or not prototypes are at sea, or for the case of a seemingly mature technology, the reasons for low market penetration (e.g., methane slips for LNG-powered ships).

3.2.3.2. Capital cost. Retrofitting ships or building new ships to operate alternative fuels or the scrubber technology is expensive. The capital expenditure (CAPEX) varies depending on the technology, the ship engine power, and the type of installation, i.e., retrofit or new build [74,75]. Authors understand that this cost also varies significantly; not all technologies are mature, and ship characteristics are not homogenous, leading to significant variation in the literature. We investigated the literature to extract values we deem consistent and indifferent to the type of installation (Table 7).

3.2.3.3. Relationship between M-TRL and Capital Cost. With future enhancements in availability and supply chain, costs reduction would foster the adoption and maturity of the technologies/fuels. Based on various economic theories, such as *economies of scale* or *learning by doing*, the more a technology matures, the more its production costs per unit decrease, these mechanisms affect the adoption of environmental technologies [78].

We studied the relationship between the technology/fuel M-TRL and the capital cost expressed in the last two sub-sections (Fig. 12). This relationship verifies a linear regression (R2 =0.7) (Fig. 12), that we used to define the future Technology Readiness Levels based on future capital

Table 7
Capital expenditure selected for each technology/fuel for the prospective work [17,76,77].

Technology /fuel	CAPEX in the literature (€2020/kW)	CAPEX selected (€2020/kW)
LNG	1076	1000
Ammonia	3195	3000
Hydrogen	4621	4500
Methanol	432	400
Scrubber	204	200

[2] The levels are defined as follows: M-TRL 1: Basic principle observed, M-TRL 2: Technology concept, M-TRL 3: Proof-of-concept, M-TRL 4: Lab validation, M-TRL 5: Prototype at sea, M-TRL 6: Pre-production, M-TRL 7: Low-scale production, M-TRL 8: Initial market introduction, M-TRL 9: Market expansion.

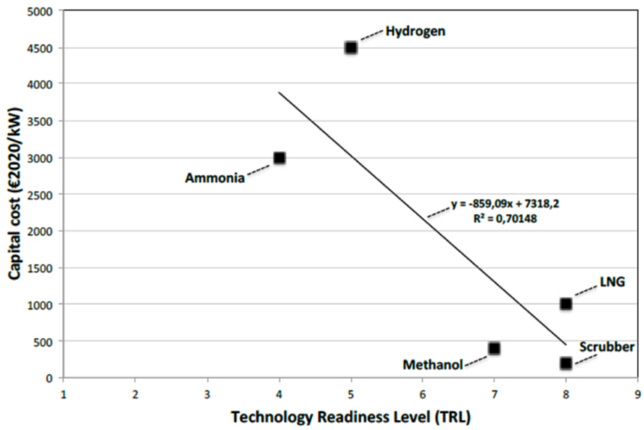

Fig. 12. Relationship between M-TRL and the capital cost. The black line represents a linear regression. Data source: [17,76,77].

costs (Table 8). Three levels of capital costs were assumed in line with possible values as identified from the literature (from level A, close to a business as usual, to level C, which represents a significant decrease in CAPEX).

3.2.4. *Fuel price projection*

This section focuses on the current and future prices of the various fuels studied in the prospective work. We do not include other operational costs in the study, as they are low compared to fuel prices and relatively similar between alternatives (i.e., fuels and scrubbers). When considering the various fuels examined in this prospective study, there exists a wide range of potential values as found in different studies (Fig. 13) [63,69,72,79–87]. These variations are probably due to the high volatility of fossil fuel prices in time (i.e., year) and space (i.e., regions), the low production and availability of alternative fuels, especially regarding renewable forms of alternative fuels. In addition, the price spread between fuels significantly differs from one study to another. For instance, LNG costs twice the price of HFO [86] in some studies, while this fuel is slightly cheaper to HFO in other studies (Table 9) [63,80]; Some studies suggest that ammonia is 10.6–30.2 times cheaper than hydrogen [88], whereas some others state a 3-time factor [85], or even a lower price of hydrogen [63]. Furthermore, one fuel can be more expensive than others in some parts of the world, whereas the opposite can occur in other regions [86].

Based on the various price values in the literature, we propose a set of values for 2020 with HFO as a baseline (i.e., baseline value from *Clarksons* data). It should be noted that the values expressed for ammonia, hydrogen and methanol are for grey or blue production (i.e., coal- or hydrogen-based production).

Table 8
2050 levels of technology readiness level (M-TRL) and capital cost (CAPEX) for each technology/fuel. Data source: [17,76,77].

Technology /fuel	Level A (in 2050)	Level B (in 2050)	Level C (in 2050)
LNG	M -TRL:8 CAPEX:1000€	M -TRL:8 CAPEX:400€	M -TRL:9 CAPEX:200€*
Ammonia	M -TRL:5 CAPEX:3000€	M -TRL:7 CAPEX:1300€	M -TRL:9 CAPEX:200€*
Hydrogen	M -TRL:6 CAPEX:2200€	M -TRL:8 CAPEX:400€	M -TRL:9 CAPEX:200€*
Methanol	M -TRL:7 CAPEX:400€	M -TRL:8 CAPEX:400€	M -TRL:9 CAPEX:200€*
Scrubber	M -TRL:8 CAPEX:200€	M -TRL:9 CAPEX:200€	M -TRL:9 CAPEX:200€*

* The value expresses the cost of retrofitting an existing ship. At this M-TRL, the cost of implementing a solution for new build is entirely integrated into the ship's cost (i.e., no additional cost).

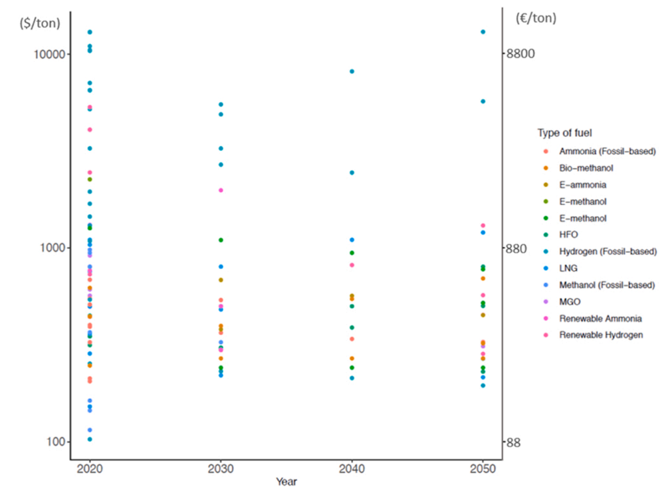

Fig. 13. Variation in fuel price depends on years and fuel types. Data source: [46,47,56,63,69,72,80,84,86,89–93].

Table 9
HFO-alternative fuel, selected fuel prices for 2020.

Fuels	Selected price in 2020(€/t)
HFO	350
LNG	300
Ammonia (grey or blue)	600
Hydrogen (grey or blue)	3000
Methanol (grey or blue)	325

3.2.4.1. *HFO.*

The projected price of conventional fuel HFO exhibits significant variations according to different studies[94]. Considering the wide range of values found in the literature, as well as the baseline value for 2020 set at 350 €/t (as shown in Table 9)[95], the projections for HFO prices can differ considerably.

HFO prices would remain stable until 2050 despite the depletion of reserves under level A (Fig. 13) [69,81]. The stability, around 350 €/t, could also be due to stable demand for fuel associated with low regulation targets (e.g., no carbon tax). In level B, HFO price would slightly increase, but this growth [94] is limited by new reserve discoveries [79]. The price would increase to 370 €/t and 445 €/t in 2030 and 2050, respectively (Fig. 13). Higher demand and new regulations can also explain the price increase. In level C, the prices continue to show a significant increase, subject to high variability. This increase could be due to the rarefaction of oil due to the depletion of reserves [83]. Also, fuel demand increases, and carbon taxes (or other incentive schemes) are enforced. In 2030, the HFO price is expected to be around 480 €/t and reach 995 €/t in 2050 (Fig. 13).[95].

3.2.4.2. *Liquefied natural gas (LNG).*

LNG fuel price historically follows the HFO price trend while lower and subject to significant variabilities [96]. We propose a baseline value in 2020 at 300 €/t.

A stable LNG price will be observed in level A until 2050 despite the depletion of reserves [69,81]. It possibly experiences a slight decrease of around 10 % per decade between 2020 and 2050 [63], i.e., 280 €/t by 2030 and 230 €/t by 2050 (Fig. 14). The prices of LNG would slightly increase in level B, but this growth [94] would be limited by new reserve discoveries [79,80,94]. The price increases to 340 €/t and 420 €/t in 2030 and 2050, respectively (Fig. 13). In level C, the price would follow the current trend of the last two decades, i.e., a significant increase, subject to high variability. This increase could be due to the rarefaction of oil due to the depletion of reserves [83]. In 2030, the price of LNG is projected to be 470 €/t, and reach 955 €/t in 2050 (Fig. 14) [95].

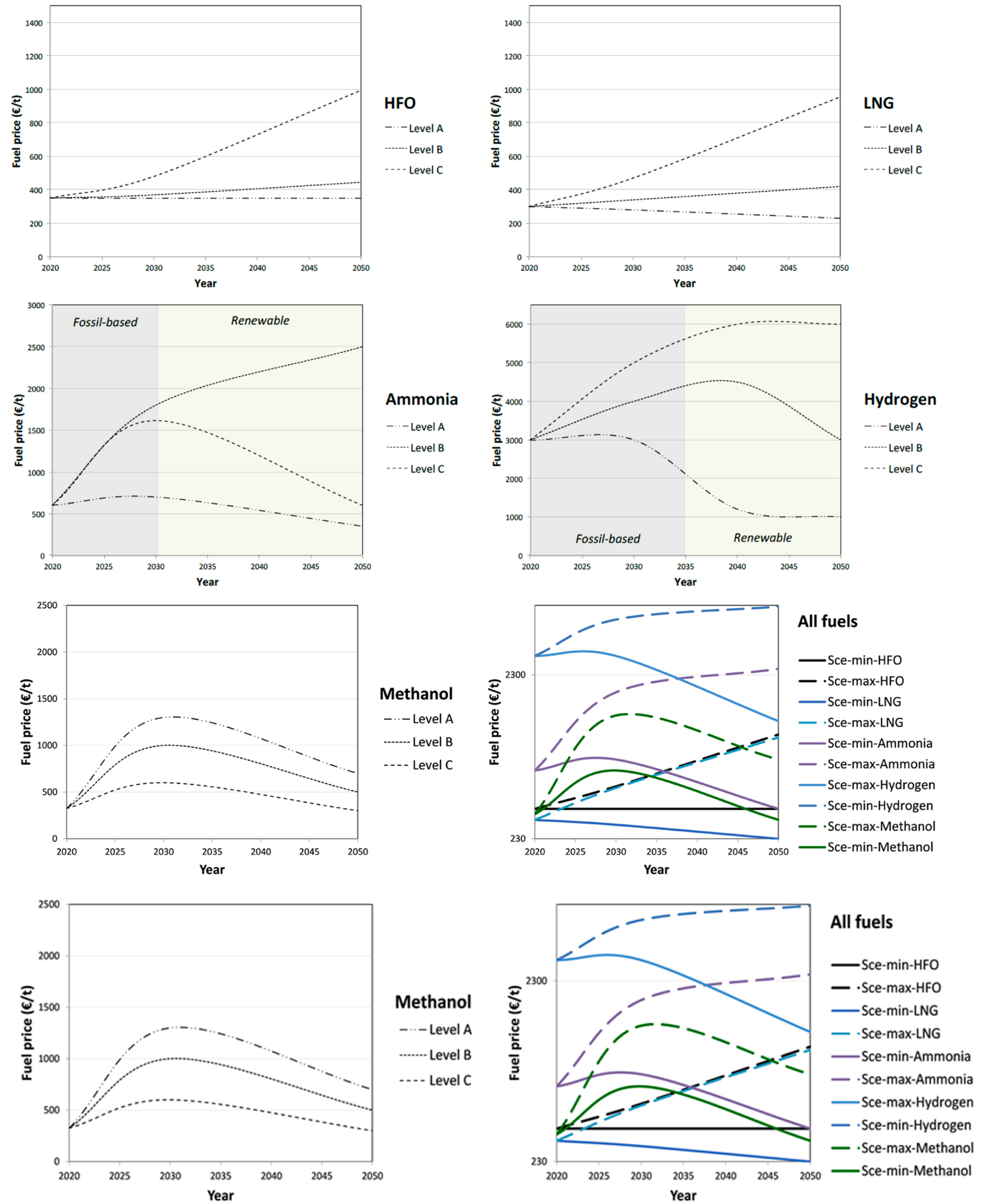

Fig. 14. Projections of the fuel prices for HFO, LNG, Ammonia, Hydrogen and Methanol. The bottom-right figure represents the minimum and maximum trends for each fuel on y-log axis. [63,69,72,79–86,94].

3.2.4.3. Ammonia. Ammonia is currently mainly used as fertiliser. The development of ammonia as a fuel for shipping is limited. Therefore, defining a price for this fuel is challenging. The values found in the literature are between 205 – 685 €/t in 2020 for fossil-based ammonia [90,93]. The projected values for green ammonia vary between 450 – 1980 €/t depending on the year [72,84]. Given these uncertainties, we chose to define a price for fossil-based ammonia (Table 9). This price would increase as over time until 2030 due to the increased share of renewable ammonia and the rarefaction of fossil fuel [83]. After this point, the evolution of the price would depend on the production cost of green ammonia [97].

Level A illustrates a slight increase in ammonia prices, but this increase would be limited by progress in green ammonia production. Therefore, after a peak in 2030 (700 €/t), the price of ammonia would decrease and reach 350 €/t in 2050 [98–100] (Fig. 14). In level B, the global price of ammonia would increase during the ramp-up period of green ammonia and reach 1800 €/t in 2030. Afterwards, we assume the price would continue growing, but at a lower rate, to reach 2500 €/t in 2050; (Fig. 14). Level C would follow the same trend as level B until 2030.However, after this point, we assume the price of ammonia to take a divergent path and decrease to 600 €/t by 2050 under level C. This divergence accounts for a potential improvement in the production of ammonia after 2030, contributing to a price decrease [84,101] (Fig. 14).

3.2.4.4. Hydrogen. Like ammonia, the lack of hydrogen-based fuel production for shipping impedes the price determination. In the literature, the prices of fossil-based hydrogen is estimated in the range of 103 – 13,000 €/t [86,90]. For renewable hydrogen fuel, in 2040–2050, the cost is estimated between 284 and 5330 €/t [63]. Given these uncertainties, we chose to define a price for fossil-based hydrogen in 2020 (Table 9). This price is assumed to increase, until 2030, due to the increased share of renewable hydrogen and the rarefaction of fossil fuel [83]. However, the growth rate would remain uncertain and alternative paths are considered. After this point, the evolution of the price will depend on the production cost of green hydrogen [97].

In level A, hydrogen prices remain almost stable until 2030 and tend to decrease afterwards to 1000 €/t in 2050 [82,86] (Fig. 14). Under level B, the global price of hydrogen increases until 2040 before decreasing back to 3000 €/t by 2050. This could be explained by the progress made in the production of green hydrogen [82,86] (Fig. 14). Level C depicts an increasing trend until 2040, but progress in green hydrogen leads to a slower growth rate and stabilises the price at 6000 €/t by 2050 [82,86] (Fig. 14).

3.2.4.5. Methanol. Methanol appears cheaper than hydrogen or ammonia. In the literature, fossil-based methanol costs between 115 and 978 €/t [90,93]. In the future, prices are expected between 241 and 1097 €/t for green methanol [56,72]. Similar to ammonia and hydrogen, we assume an increase in prices in the next decade associated with the decline of fossil energy reserves and an increase in the demand for green methanol. After this point, the prices should quickly decrease in all scenarios, given that methanol infrastructures are more developed than ammonia and hydrogen. Levels A, B and C thus exhibit the same pattern, i.e. price increase followed by a peak around 2030 and a decline, the major difference being the magnitude of the price evolution.

In level A the price increase would be the most significant in the first decade, peaking at about 1300 €/t in 2030 and decreasing to 700 €/t in 2050 [72] (Fig. 14). In level B, the peak and 2050 prices would be 1000 €/t and 500 €/t, respectively [72] (Fig. 14). Under Level C, the price of methanol would reach 600 €/t in 2030, followed by a reduction leading to the same level as fossil-based methanol in 2020, which is 300 €/t, by 2050 [72] (Fig. 14).

3.2.5. Regulation and incentives

To reduce shipping emissions, two main approaches are used: regulations and incentives. Regulations enforce mandatory policies that require the shipping industry to adopt greener practices. Incentives, on the other hand, motivate companies to voluntarily embrace eco-friendly solutions. Both can be implemented at global and international level, as well at a regional and national level.

3.2.5.1. Global/International. The main regulatory framework to reduce emissions is the International Maritime Organization (IMO) International Convention on the Prevention of Pollution from Ships (MARPOL)[102]. Annex VI of MARPOL sets limits for SOx and NOx emissions globally and in Emission Control Areas (ECAs) [103]. The sulphur content of fuel oil used on ships is restricted to 0.50 % m/m worldwide and 0.1 % m/m in ECAs. The carriage of non-compliant fuel oil for combustion purposes is prohibited [104].The IMO's Marine Environment Protection Committee has adopted a strategy to reduce GHG emissions by 50 % by 2050 compared to 2008 levels[69,105]. This strategy is scheduled for revision in 2023 [106].

To optimize gas emissions, the IMO introduced the Data Collection System (DCS) requiring ships over 5000 tonnes to collect consumption data [105]. Flag states must collect and aggregate the data and submit it to the IMO. The Energy Efficiency Design Index (EEDI) sets minimum energy efficiency standards for new large vessels. It mandates improvement steps depending on vessel type: 10 % in 2015, 20 % in 2020, and 30 % in 2030 compared to vessels built between 2000 and 2010 [107]. The Ship Energy Efficiency Management Plan (SEEMP) complements the EEDI by developing ship-specific plans and strategies (e.g., speed optimisation) [108].The European Union supported this mechanism in 2019 [109].

3.2.5.2. Regional. Several EU regulations shape the regulatory framework of the Baltic Sea region (BSR). The EU Directive 2012/33 and 2016/802 restrict the use of marine fuels with sulphur content exceeding 3.50 % within the EU territory, except for ships using emission abatement methods. [110,111]. The EU implemented the Monitoring, Reporting, and Verification (MRV) regulation in 2015, requiring ships above 5000 tonnes to report CO2 emissions based on fuel consumption.[112]. This regulation anticipated the one by the IMO i.e., DCS [105]. This regulation was progressively enforced starting in 2018 with the implementation of requirements to monitor (1st January 2018) and report the emissions using compliance documents (from 2019).

In 2019, the MRV regulation was amended to include a global data collection system for ship fuel oil consumption and set a target of reducing annual CO2 emissions per transport work by at least 40 % by 2030. [109]The Commission should ensure compliance with such measures through financial penalties fixed by the Member States, which shall be effective, proportionate, dissuasive, and compatible with a market-based trading emission system[109]. EU Directive 2019/883 encourages measures such as discharge bans for wastewater from open-loop scrubbers in territorial waters [113]. This measure imposes, therefore, the installation of scrubber waste facilities in ports. The EU Green Deal, adopted in 2019, aims to reduce GHG emissions by 55 % by 2030 and achieve climate neutrality by 2050[114].As a part of the EU 2030 Climate target plan [115], The Sustainable and Smart Mobility Strategy targets renewable and low-carbon fuels representing 6–9 % by 2030 and 86–88 % by 2050 in the maritime transport fuel mix.[116]. The EU's more ambitious European Climate Law, adopted in 2021, includes proposals like the "Fit for 55" package, FuelEU Maritime, and the Trans-European Transport Network (TEN-T) to advance sustainable transport.

3.2.5.3. National. The BSR countries have to enforce IMO and EU regulations. Most countries have acted to reduce sulphur emissions. One can observe a high heterogeneity in sanctions proposed by the BSR countries (Table 10). Maximal financial sanctions range from €2900 to €1000,000 depending on the country and can reach €6000,000 in

Table 10
Summary of sanction for non-compliant ships with sulphur regulations in the BSR [117-119].

Countries	Financial sanctions (maximal; €)	Penal sanctions
Denmark	~50,000	2years imprisonment Ship detention
Finland	~800,000	
Germany	~22,000	
Latvia	2900	
Lithuania	~14,481	
Norway	~25,000	Criminal actions
Norway	~25,000	Ship detention
Sweden	~1000,000	Ship detention
Belgium	−6000,000	

countries just outside the BSR (i.e., Belgium). It should be noted that some countries, such as Denmark, have taken the approach that the penalty should be equal to the cost advantage that the carrier had on that voyage [117]. In the BSR, 3146 ships were inspected in 2019, according to the THESIS website,[3] for 3649 inspections. Ninety-nine ships were deficient according to the MARPOL Annex VI [102], i.e., 3.1 % of ships. This number is similar to the one found by [118] for the BSR, but this study only considered non-compliance to sulphur regulation. Therefore, as MARPOL Annex VI covers other types of pollution, it would appear that compliance to sulphur emissions increased between 2016 and 2019 (or compliance to other emissions increased). The comparison between the THESIS and HIS databases shows that 36 % of the ships crossing the BSR region are inspected.[4]

In addition, in light of environmental side effects (i.e., the release of chemicals in the water), the use of open-loop scrubbers has been restricted by some countries by applying partial banning of this technology (Table 11).

A recent and possible future narrative of the regulations and incentives are provided in Table 12, under different levels and influencing factors.

4. Results and discussions: scenarios narrative

4.1. Scenario generation and transfer

The final situation described in this section reflects on the combination of scenarios obtained in Fig. 15, i.e., even if the narrative of each scenario is not the same, the final situation is similar. As a reminder, the narrative of this section is "a description of a potential future situation, including the path of development leading to that situation"[30].

Table 11
Summary of open loop scrubber restrictions in the BSR [120,121].

Countries	Ban application
Denmark	in three ports
Estonia	in all ports
Finland	in Port of Porvoo
Germany	in inland ports and waters
Latvia	in territorial and port waters
Lithuania	in all ports
Norway	in Fjords
Russia	in two ports
Sweden	in several ports

[3] Website gathering results from the MRV regulation.

[4] We chose the values for the year 2019 instead of 2020, as the COVID crisis seems to have affected the number of inspections.

4.1.1. Scenario 1

This scenario represents the best-case scenario for achieving the IMO's emission reduction targets with minimal environmental impact (Fig. 16). Despite a slight increase in worldwide shipping emissions in the 2020 s, the implementation of stronger EEDI regulations and EEXI by 2025 improves ship efficiency and limits emissions growth. The banning of HFO in the BSR ECA by 2040 accelerates the decline of this fuel, which was already low in usage. Other fossil-based fuels like distillate fuel, LSFO, VLSFO, and LNG also decrease between 2030 and 2040 due to various factors, including methane slips affecting LNG's emission benefits.

The production of alternative green fuels significantly rises in the BSR due to stronger regulations and geopolitical factors such as the war in Ukraine. The transition from grey (conventional) production to blue (carbon capture and storage) or green (renewable) production increases notably, driven by the implementation of the EU ETS for well-to-tank emissions. Initially, grey production boosts the market penetration of alternative fuels, but it is gradually replaced by blue and green production between 2030 and 2040. Hydrogen emerges as the most widely used fuel for maritime transportation, followed by ammonia and methanol. By 2040–2050, these three fuels become the primary options for shipping in the BSR.

4.1.2. Scenario 2

This scenario assumes a delay in the maturity of alternative fuels, with a focus on biofuels and limited technology diversification (Fig. 16). Stronger EEDI regulations and EEXI by 2025 help mitigate emissions growth. However, due to a lack of political will, no stricter regulations are implemented at the international, regional, or national level. Fossil fuel prices rise due to international conflicts and resource depletion. HFO consumption decreases, while LNG faces challenges due to environmental concerns. Distillate fuels such as LSFO and VLSFO, along with end-of-pipe solutions, are predominantly used in the BSR. Ammonia and hydrogen technologies experience setbacks, leading to delays in their maturity and no reduction in capital investment costs. However, the industry responds by developing methanol and other biofuels as alternatives. In 2050, ammonia and hydrogen account for only 20 % of fuel usage, while methanol and biofuels are utilized in 55 % of BSR ships.

4.1.3. Scenario 3

This scenario assumes a delay in technology maturity and a transition driven by strong regulations (Fig. 16). The implementation of stricter EEDI regulations and EEXI by 2025 will lead to emission reductions. The banning of HFO in the BSR ECA by 2040 accelerates the phasing out of this fuel. While renewable energy production increases in the BSR, the initial prototypes of ammonia and hydrogen face delays and decreased capital investment costs. However, stricter national laws and higher fossil fuel prices drive shipping companies to invest in ammonia and hydrogen despite the high costs. LNG becomes more prevalent as methane slip issues are partially resolved by 2040, serving as a transitional fuel due to its lower investment costs. Methanol also contributes to meeting international emission targets without being subject to national sanctions.

4.1.4. Scenario 4

The assumption of delay in technology maturity, coupled with weak regulation and low diversification, results in the worst-case scenario (Fig16). This scenario fails to achieve the emission targets and is considered the least environmentally friendly. Although the renewable energy produced in the BSR significantly increases (~80 % of the electric production in 2050), the absence of reliable technology for alternative fuels means that distillate fuel, LSFO, and VLSFO continue to be primarily used. In 2050, almost half of the ships in the BSR still use fossil-based fuels due to significant delays in the maturity of ammonia and hydrogen, a lack of anticipation and development of biofuels. LNG fails to increase its market share due to persistent methane slip issues

Table 12
Regulation and incentives summary for factor and levels [106,107,122,123].

Code		RI-1	RI-2	RI-3	RI-4	RI-5	RI-6
Factor		**Global Regulation**	**International Regulation**	**Regional Regulation**	**Global Incentive**	**International Incentive**	**Regional Incentive**
2020		2013: EEDI 2016: SEEMP 2018: IMO GHG Strategy 2019: DCS 2020: Global Sulphur Cap	2012 & 2016: EU Directive 2012/33 and 2016/802 2015: MRV Regulation 2019: Global data collection system for ship fuel oil consumption 2019: EU Directive 2019/883 2020: Sustainable and Smart Mobility Strategy 2020: EU Green Deal	Sanctions for noncompliant ships to IMO Sulphur regulations: Maximum from €2.9 to €1,000k -Restriction of OL scrubbers: Partial banning in some countries -Ship inspections: Around 35 % of ships crossing the BSR are inspected.	No incentive reported	2014–2020: European Fund for Strategic Investments (EFSI)= € 245 billion	Differentiated port fees 17 % of BSR ports -Differentiated fairway dues 20 % of countries -Funding Norwegian NOx Fund
2030	**A**	Nothing to report	Nothing to report	Nothing to report	Bunker levy price: 0€/t	10 % budget decrease in EU fundings from 2020 levels	17 % and 20 % of major ports and countries propose emission based incentives -No homogenisation of rebates
	B	2022: EEDI Phase3/Tranche1 2023: EEXI & SEEMP for old ship 2025: EEDI Phase3/Tranche2	2022: Enforcement of ETS	2025: Prohibition of OL scrubbers in the BSR 2030: Homogenisation of Sulphur sanctions= €250k 2030: 50 % of ships crossing the BSR are inspected.	Bunker levy price: 32€/t	10 % budget increase in EU fundings from 2020 levels	30 % of major ports and countries propose emission based incentives -No rebates homogenisation
	C	2022: EEDI Phase3/Tranche1 2023: IMO GHG (i.e., stricter) 2023: EEXI and SEEMP for old ships 2025: EEDI Phase3/Tranche2	2022: Enforcement of ETS	2025: Prohibition of OL scrubbers in the BSR 2030: Homogenisation of Sulphur sanctions= €1,000k 2030: 50 % of ships crossing the BSR are inspected.	Bunker levy price: 50€/t	20 % budget increase in EU fundings from 2020 levels	30 % of major ports and countries propose emission based incentives -Rebates homogenisation
2050	**A**	Nothing to report	Nothing to report	Nothing to report	Bunker levy price: 0€/t	34 % budget decrease in EU fundings from 2020 levels	17 % and 20 % of major ports and countries propose emission based incentives -No homogenisation of rebates
	B	Nothing to report	Nothing to report	2035: Prohibition of CL scrubbers in the BSR 2040: Homogenisation of Sulphur sanctions= €500k 2050: Homogenisation of Sulphur sanctions= €750k	Bunker levy price: 160€/t	46 % budget increase in EU fundings from 2020 levels	100 % of major ports and countries propose emission based incentives -No homogenisation of rebates
	C	2040: Ban of HFO in internation	Nothing to report	2035: Prohibition of CL scrubbers in the BSR 2040: Homogenisation of Sulphur sanctions= €2000k 2040: Ban of HFO in BSR waters. 2050: Homogenisation of Sulphur sanctions= €3000k	Bunker levy price: 250€/t	107 % budget increase in EU fundings from 2020 levels	100 % of major ports and countries propose emission based incentives - Homogenisation of rebates

and gradually reduces to an insignificant amount. However, methanol shows consistent growth, but it is not enough to replace and mitigate the impacts of fossil fuels.

The first scenario (Green shipping in 2050) has been deemed the most likely to happen by the stakeholders focus groups. The main advantageous factors characterising this scenario are strong international regulation, a high diversification of energy sources and a high maturity of alternative fuels and technologies. Ammonia, hydrogen and methanol are expected to dominate the BSR market, with each fuel penetrating approximately one-third of the fleet (more precisely, 30 % for methanol and 35 % for each of ammonia and hydrogen). The increased market penetration of these alternative fuels is accompanied by a decrease in the capital investment costs for equipping vessels, especially for hydrogen, with a decrease of about 90 %. In 2020, no ship in the BSR was fuelled with hydrogen or ammonia, and there was only one methanol ship. Hence, attaining the market penetrations predicted by this scenario in 2050 would require about 1.7 million €/kW,[5] assuming an unchanged total fleet size. The available funds for green shipping (e.g. European Union, European Investment Bank) could support these investments; however, the effectiveness of these funds may be limited. While some of our stakeholder panellists find that companies underuse those funds, others feel a lack of financial support. The perceptions of lack of information and insufficient support from our panel are consistent with the literature, which identifies them as significant barriers to adopting alternative shipping fuels [124].

Regarding the price of these fuels, a substantial decrease is projected,

[5] All monetary values are expressed in nominal (current) currency, i.e. without adjusting for projected inflation levels.

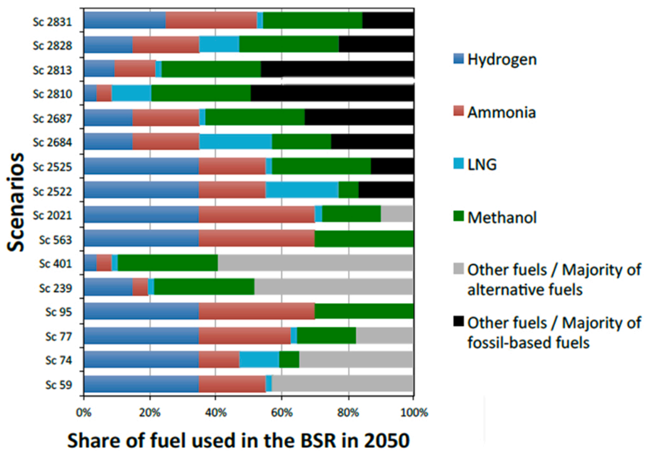

Fig. 15. Share of fuel used in the BSR in 2050 based on the initial scenarios (Other fuels/majority of fossil-based fuels representing extensive use of end-of-pipe technologies (e.g. EGR, SCR, CC).

with hydrogen being the front-runner. The price for hydrogen would reach 700 €/t in 2050, from 3 000 €/t in 2020, while methanol and ammonia would show a small and no price decrease, respectively. The global fuel price for the BSR fleet would be 615 €/t, an increase from the 2020 situation, with an average of 480 €/t (weighted average for all fuels present in 2020 and 2050). This result indicates that in the case of Scenario 1, it will cost 28 % more to fuel the vessels in 2050 compared to 2020 (for the same fuel consumption in tonne and for unchanged fleet size). A more optimistic situation would have included a substantial reduction in the price of ammonia (below415 €/t) and would have led to a status quo in terms of average fuel price (maintained at the 480 €/t level of 2020), but our scenario did not predict such. However, considering the emission performances of the fuel mix of Scenario 1 (hydrogen – methanol – ammonia), the limited economic advantages might be mitigated.

Scenarios 2, 4 and 3 were followed by Scenario 1 regarding their likelihood of happening. They mutually share common projections in terms of fuel prices and capital investment costs but differ in market penetrations and differ with Scenario 1, which did not project a decrease in the price of ammonia as a fuel. Scenario 2 is characterised by a strong market penetration of methanol (30 %) and biofuels (23 %), followed by hydrogen (15 %); while Scenario 3 and 4 are marked by the persistence of LNG (22 %) and VLSFO/LSFO (38 %) respectively. Stakeholders graded these scenarios as lesser likely than scenario 1 because of the high projected penetration of biofuels (for Scenario 2), which is deemed unsustainable from a production perspective; because of the long-term persistence of LNG (for Scenario 3), which is perceived as a transitional solution given the methane emissions. Furthermore, the potential utilization of HFO and distillates as barriers to achieving the 2050 decarbonization target led to diminished assessments of Scenario 4. Overall, the regulation levels were deemed plausible if they followed the identified abatement solutions' technological improvement and feasibility. In fact, very stringent regulatory pressure beyond technical feasibility would paralyse the shipping industry and international trade.

Involving stakeholders representing the sustainability section of the shipping industry in the selection of realistic scenarios for green shipping has its risks and challenges. While their expertise and dedication to sustainability are valuable, sustainability groups often push for ambitious emission reduction targets. It is crucial to strike a balance between setting ambitious goals and ensuring the chosen scenarios are grounded in technological readiness, infrastructure feasibility, and economic viability.

The implementation of methanol, hydrogen and ammonia as alternative fuels in ships presents several technological, economic, and regulatory challenges, all of which need careful evaluation to determine their feasibility in maritime decarbonization strategies. Methanol has drawn attention for its lower carbon emissions compared to conventional marine fuels [27], but its lower energy density [29] requires larger fuel storage capacities on ships and more frequent refuelling[26]. Additionally, methanol infrastructure at ports remains underdeveloped, limiting its global availability, and it is still predominantly produced from fossil fuels like natural gas [125], raising sustainability concerns unless the production transitions to green methanol. Safety risks such as methanol's toxicity and corrosiveness also pose hazards in handling and storage[27]. Hydrogen offers zero-emission potential when used in fuel cells [126], but its low volumetric energy density necessitates advanced storage solutions[127]. The high production cost of green hydrogen [128], coupled with scarce refuelling infrastructure at major ports, further impedes its adoption. Moreover, fuel cell technology for large-scale maritime use is still in its early stages, and hydrogen's flammability raises significant safety concerns during storage and handling[129]. Ammonia is also a promising carbon-free fuel[130], but it poses safety risks due to its toxicity and corrosiveness, which threaten both crew members and port workers[131]. Ammonia combustion engines require modifications and may still produce nitrogen oxides (NOx) unless emissions control technologies are employed[132]. Similar to hydrogen, green ammonia production is limited, and its global refuelling and storage infrastructure is underdeveloped [29]. Without coordinated policies and technological advancements, integrating these alternative fuels into the shipping industry on a large scale will remain challenging.

5. Conclusion and perspectives

The study aimed to develop the fuel mix scenarios to mitigate shipping emissions and meet IMO's 2050 target of decarbonisation of BSR's shipping sector. The scenario development is driven by the technology availability, maturity, fuel price, energy mix and regulation, which are assessed for HFO, distillates, LNG, Hydrogen, Ammonia and Methanol as fuel. Role Abatement technologies such as scrubber are also assessed. Currently, fossil fuel consumption in the BSR has been increasing slightly each year due to global bunker requirements, but the share of HFO is decreasing in favour of distillate fuel, LSFO, VLSFO, or LNG. The price of HFO, which affects the price of other fossil-based fuels, is high due to the international context (i.e., the war in Ukraine). While stabilization is expected in the short term, the price is anticipated to increase gradually in the future as reserves deplete. Although the BSR shipping fleet seems to be stable, the size of ships is expected to increase by 8 % per year and so will the energy consumption.

The limited availability of alternative fuels and issues related to methane slips with LNG, which led to the cancellation of LNG at several ports could prompt fuel diversification. While methanol bunkering is merely developing in the BSR, several hydrogen projects are emerging at around 21 maritime BSR ports, which could provide a better long-term alternative. Though limited, projects for ammonia are also emerging. Possible breakthroughs in hydrogen and ammonia-fuelled ship prototypes could help meet the 2050 decarbonization targets. The Capex could range between 200 and 3000 euro/kW for Ammonia and Hydrogen with fuel price ranging between 350 and 2500 euro and 100–6000 euro respectively. However, without a tangible alternative fuel infrastructure, the sector is encouraging closed-loop scrubber discharge facilities, which could reach to 85 % of 139 major ports in the region, while open-loop scrubbers are gradually being phased out due to partial bans in seven BSR countries. Until then, supporting strategies adopted within the purview of IMO 2050 targets, such as financial sanctions, should be monitored and judicially implemented. breach. Based on the expected regulatory changes and trends in the adoption of alternative fuels and technologies, our scenarios depict the plausible pathways to the mitigation of shipping emissions in the BSR in 2050. Scenario 1 is the most environmentally optimistic, with the fleet being fully fuelled by hydrogen (35 %), ammonia (35 %), and methanol (30 %). On the other extreme, under Scenario 4, the persistence of

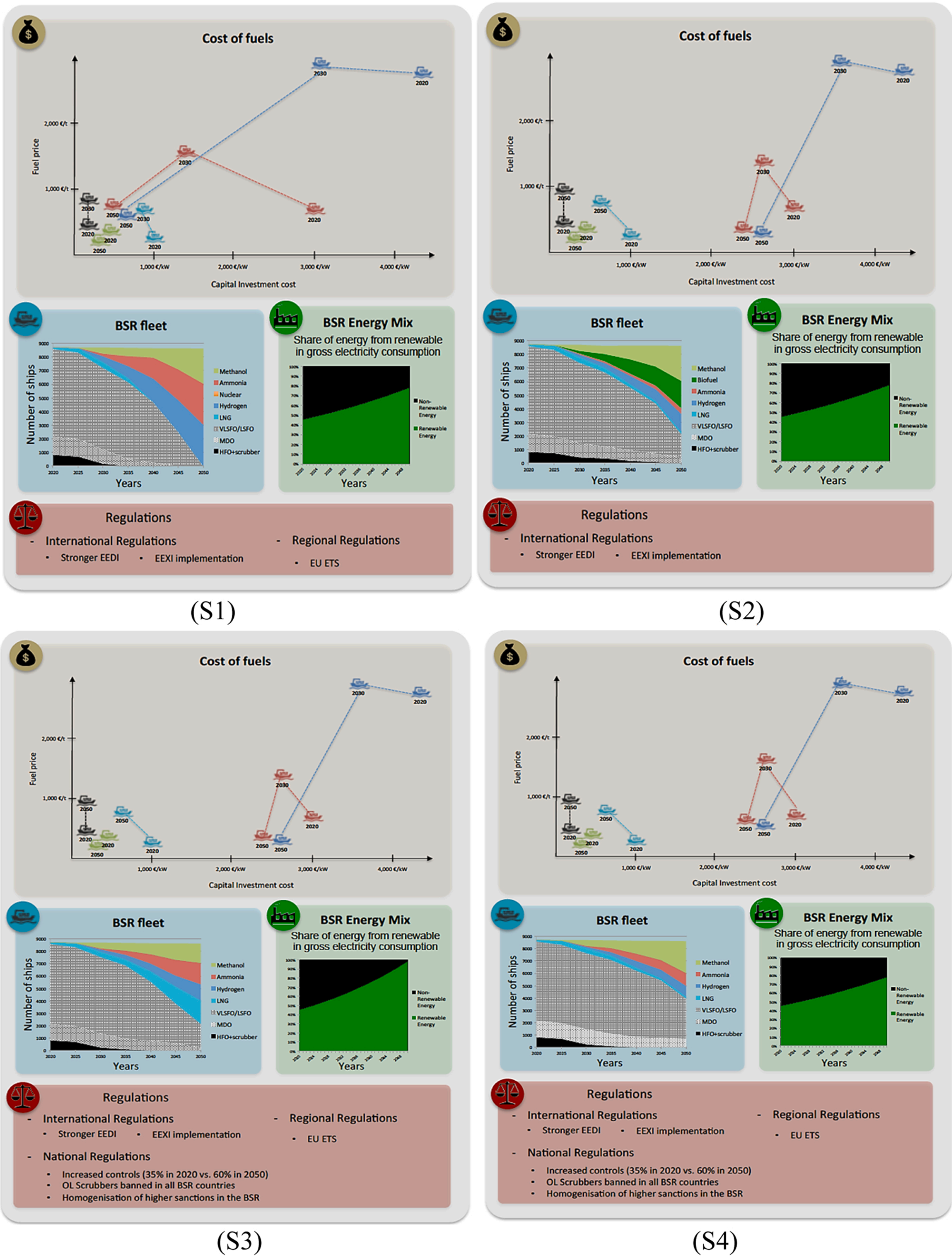

Fig. 16. Scenario S1-S4(Left to Right) deduce from 16 scenarios presented in Fig. 15: Scenario1- The final situation described reflects on Scenarios 95 and 563; Scenario 2- The final situation described reflects on Scenarios 239 and 401 presented in Fig. 15; Scenario 3- The final situation described reflects on Scenarios 59, 74, 2522 and 2684 presented in Fig. 15; Scenario 4-The final situation described reflects on Scenarios 2687, 2810 and 2813 presented in Fig. 15.

VLSFO/HFO and MDO maintains the shipping industry closer to a BAU case i.e. ~50 % market share, of despite the steady adoption of alternative fuels like methanol (30 %). Although scenario 1 presents practical challenges such as safety and storage constraints as well as high prices (average price for the fuel mix of S1 being 28 % higher than BAU), stakeholders remain optimistic about achieving the decarbonization targets with significantly reduced harmful emissions in shipping. Their confidence in scenario 1 reflects a similar sentiment. By discussing and addressing potential limitations and obstacles, stakeholders can work towards realistic and feasible scenarios for green shipping that consider the practicalities of technology, infrastructure, and economic factors.

Further research and analysis are necessary to enable the shipping sector to contribute to the global decarbonisation challenge. Academic research has an opportunity to provide knowledge, analysis, and optimal solutions to the shipping industry and help it navigate through the challenges of environmental degradation and climate change. This paper makes efforts to provide comprehensive scenarios that allow the shipping industry to maximize its contribution to global economic development while mitigating climate change and environmental issues. The next logical step is to model the short-term and long-term ocean and atmospheric impacts (e.g. health and non-health impacts based on emission inventory) derived from these scenarios, enabling policymakers and stakeholders to make informed decisions.

CRediT authorship contribution statement

Rohan Kumar: Methodology, Data curation, Writing – original draft, Formal analysis, Writing – review & editing, Investigation, Conceptualization. **Maxime Sebe:** Methodology, Conceptualization, Supervision, Data curation, Formal analysis, Writing – review & editing, Validation, Writing – original draft. **Fabien Yao:** Investigation, Validation, Writing – review & editing, Methodology, Writing – original draft. **Recuero Virto Laura:** Writing – review & editing, Supervision, Funding acquisition, Resources, Conceptualization. **Kent Salo:** Methodology, Writing – review & editing, Conceptualization, Investigation. **Shams Al-Hajjaji:** Investigation, Writing – original draft, Writing – review & editing. **Dennis Booge:** Methodology, Writing – review & editing. **Christa Marandino:** Conceptualization, Writing – review & editing, Resources. **Nele Matz-Lück:** Supervision, Writing – review & editing. **Anna Rutgersson:** Supervision, Methodology, Conceptualization, Project administration, Writing – review & editing, Funding acquisition.

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Data availability

Data will be made available on request.

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