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# A transition towards clean propulsion in shipping: The role of PESTLE drivers and implications for policy

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ABSTRACT

In the context of the ongoing green transition within the maritime sector, this study seeks to explore the interplay of factors influencing the development of clean propulsion technologies. We identify the drivers underpinning the shift towards cleaner propulsion in maritime operations and outline the implications for the future of such technologies. This research is a result of industry-academia effort to develop a collective vision and strategy for a consortium of companies within propulsion sector. The market drivers are identified as part of a technology roadmapping process following PESTLE framework. Additionally, we employ the MICMAC method to discern dependencies and influences among these drivers. The findings indicate that certain drivers, such as fuel pricing and economic incentives, wield considerable independent influence, whereas others, including green financing, political will, and emission targets, exhibit substantial influence but are interdependent with other variables. Overall, most of the 30 drivers identified in the study both influence and depend on other drivers, creating a complex and uncertain system. This research contributes empirically to a holistic understanding of the intricate interplay among diverse market drivers in the context of clean propulsion in the maritime sector. Theoretically, it unveils the interdependent structure of socio-technical regimes and its implications in terms of "windows of opportunity" for niche development.

## 1. Introduction

Maritime transportation has long been excluded from the efforts to abate climate change due to the international nature of shipping, its backbone role in the world economy, unclear regulatory responsibilities, and challenges in attributing emissions from shipping to particular states or actors [1,2]. While pollutant emissions such as nitrogen oxides, sulphur oxides, and particulate matter have been regulated in the sector to a certain extent, greenhouse gas (GHG) emissions have not been scrutinized until recently. Nevertheless, much political attention has recently been drawn to including maritime transport in mitigating climate change and other social life industries and sectors [3,4]. In July 2023, the International Maritime Organization (IMO) updated its strategy to reduce greenhouse gas emissions from international shipping by aiming for net zero emissions by 2050.

There are many options and certain freedoms for shipowners and operators to choose paths to reach decarbonization goals. The wide array of solutions for abating GHG emissions in shipping includes ship design and operational and technological solutions [5]. In this article, we focus on 'clean propulsion technologies', which include technologies implemented in ship propulsion systems and reduce GHG emissions from ship operations.

Legal frameworks and regulations, especially the financial incentives they create, are often considered the foremost market drivers or push mechanisms for the transition to clean shipping [6,7]. The situation is complex, and many different drivers may impact it. For example, technological advances and many abatement solutions create another kind of push mechanism, like autonomous vessel technologies [8-10]. Various other incentives and pull mechanisms are also in play [11]. We argue that these drivers should be considered separately and simultaneously (e.g., political, economic, technological, ecological, and social). Indeed, such understanding is still missing and calls for further research.

Against this backdrop, this paper aims to untangle the above interrelation by exploring the drivers for clean propulsion in the maritime

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sector and then identifying the implications for the future of clean propulsion technologies. Through this analysis, we shed light on the direction for the development path of propulsion technologies and complementary solutions within the green transition happening in the maritime industry.

The study is based on the research within an industry-academia research project aimed at developing a shared vision and strategy for a cluster of global companies within the clean propulsion sector. Analyzing the drivers for clean propulsion was performed as a part of an effort to create an industry roadmap. Thus, we rely on the technology roadmapping process [12] and structure the results following the PESTLE framework. We further analyze the interdependencies among the identified PESTLE drivers using the MICMAC method for structural analysis to identify the most influential drivers. We contribute with a systemic analysis of the elements of a socio-technical regime in the context of green transition in the maritime sector.

## 2. Green transition in the maritime sector

Many studies are devoted to the techno-economic and regulatory aspects of the green transition in shipping. The first stream of literature concerns the transition scenarios and the conditions for realizing each scenario [13,14]. The second stream includes reviews of various measures and technologies capable of making shipping sustainable, often focusing on decarbonization [11,5,15]. The third stream of literature concerns more specific technologies and their role in the green transition [16-19]. However, the transition and its drivers have received less attention [20].

Studies also stress the social transition required for sustainable shipping. For example, Pettit et al. [21] have explored whether technological and operational innovations in shipping can lead to a substantial and swift reduction in carbon emissions. They argue that, while helpful, technologies or operational innovations that reduce the environmental impact of shipping do not represent the required socio-technical system regime shift in international maritime logistics to contribute to improved sustainability. Adopting the multi-level perspective of socio-technical transitions [22,23], the authors consider 'eco-ships' a niche that cannot change the landscape in the shipping industry. Instead, a more profound change in the production and consumption systems is needed to achieve sustainability. In a study on green shipping practices, Lai et al. [24] touch upon the institutional character of transition in the maritime sector. They state that the most prominent institutional drivers for making shipping companies adopt greener practices are regulatory or normative, expressed as shipper requests.

Transport systems are prime examples of socio-technical systems. Hence, socio-technical transition frameworks are commonly used to study transportation and mobility changes. Although Geels' [22] landmark article used the transition from sailing ships to steamships as a case in point, maritime transport has received limited attention in sustainability transition research [20]. However, a small but increasing body of knowledge is building up (e.g., [20,21,25]).

Our study explores the evolving socio-technical regime related to the 'clean propulsion technologies' niche. Like the powertrain industry's evolution in the automotive context [26], the propulsion technologies in the maritime sector will likely undergo a co-evolution; there will be a certain symbiosis of old and new technologies, while others will be replaced. While this study does not analyse the socio-technical regime shift in detail, we explore the landscape and regime level of the corresponding socio-technical system by analysing the interdependence among various drivers affecting the development of propulsion technologies in the maritime sector. More specifically, we identify how 'windows of opportunity' [22] are created due to the interplay of these drivers.

Moreover, the existing technology base for ship propulsion and complementary technologies and solutions create an institutional barrier to a swift transition to new fuels, such as existing (fossil) fuel infrastructure. As experts indicate, internal combustion engines (ICEs) are here to stay, at least for a while, and the jump to, e.g., full electrification is unlikely in deep-sea shipping due to the long distances and high energy density requirements. Indeed, shipping belongs to the so-called hard-to-abate sectors [27]. Thus, we provide a detailed analysis of the drivers for the maritime propulsion sector instead of only focusing on future marine fuels and alternative propulsion (like wind power or electricity) or regulatory drivers and techno-economic assessments of various technologies (as many studies have done), including radically innovative and incumbent ones.

## 3. Research setting and methodology

### 3.1. Research setting

This paper's qualitative study was performed within an industry-academia collaborative project (2020–2023) devoted to developing clean propulsion technologies. The project involved business partners, including engine manufacturers, a shipyard, after-treatment solution providers, and research organizations—the project aimed to create a shared vision and sustainable business solutions for the national powertrain industry.

An established technology roadmapping (TRM) technique was chosen to develop such a vision [12]. The approach provides a structured means for exploring and communicating the relationships between evolving and developing markets, products, and technologies over time [12]. A technology roadmap essentially strives to align commercial and technological perspectives by balancing and connecting market pull (the 'why') and technology push (the 'how') forces at play to uncover challenges and opportunities in technology development [28].

This paper presents the analysis of the market drivers (i.e., the pull mechanisms) and uncertainties that affect the propulsion ecosystem, steer the direction of the technology development, and draw implications for the future requirements towards the propulsion solutions in the maritime industry and maritime policy.

### 3.2. Data collection

Technology roadmapping is commonly performed in a set of workshops covering the roadmap's different layers and finding interconnections among them; for example, the definition of market drivers is usually done during the first workshop [28]. However, given the complexity of the task, we performed two workshops devoted to market drivers, supported by extensive data collection and analysis before, between, and after the workshops. During interviews, we asked respondents to identify key drivers for developing clean propulsion in shipping, specifically for the companies. We validated and refined the list of most influential drivers during a workshop and voting during a joint seminar. During the second round of interviews, we collected data on the implications of different drivers for particular companies, which were further verified in a collaborative workshop. Table 1 details the various data collection activities performed during this study.

As this study relies on qualitative data primarily gathered through interviews and discussions with a limited group of stakeholders, subjectivity is a concern. To address this, we employed multiple strategies. First, we engaged representatives from various companies and research organizations within the project consortium (as detailed in Section 3.1). Second, we employed data triangulation to recognize potential knowledge limitations among these representatives, including sectoral and regional constraints. This involved supplementing workshop and interview data with global secondary data. Third, data collection spanned over a year, allowing us to uncover evolving trends and cross-verify information, ensuring response consistency.

This approach allowed for identifying the links between global trends, local changes, and the possibilities and developments within the propulsion sector. The respondents could share the knowledge of some

**Table 1**
Data sources and collection process.

| Type of Activity | Purpose | Participants or data sources | Timeline | Outcome |
|---|---|---|---|---|
| Semi-structured interviews regarding market drivers | Understanding which drivers are relevant for different clean propulsion-related companies. | 8 companies | October 2021 | A list of market and business drivers identified by various relevant companies. |
| Workshop 1 | Collecting ideas on market drivers from project partners. | 10 companies; 8 research organizations | November 2021 | A refined and validated list of market drivers for the clean propulsion sector. |
| Online voting | | 22 responses | November 2021 | Prioritization of market drivers |
| Interviews regarding product features in the clean propulsion sector | Understanding the relevance of market drivers for particular companies. | 13 companies | February – March 2022 | Priorities of individual companies in developing propulsion technologies. |
| Workshop 2 | Validating identified drivers and identifying implications for the clean propulsion sector. | 4 companies; 4 research organizations | May 2022 | Directions for technology development in the clean propulsion sector. |
| Secondary data collection | Confirming that identified market drivers reflect the sector-wide discourse, filling in knowledge gaps. | Webinars Industry reports Policy documents | November 2021 – December 2022 | Validation of identified market drivers; new drivers identified. |

drivers that affect their businesses that were not to be found in the reviews of sector-wide trends. In that sense, we could capture the implicit knowledge of where the clean propulsion sector is heading and how it is path-dependent.

### 3.3. Data analysis

We utilized the PESTLE framework to organize and analyze the trends and drivers for clean propulsion in a structured manner, allowing us to categorize the drivers in the following thematic topics:

- P – political drivers (What are the political factors and drivers nationally, in the European Union, and globally? How can these factors and drivers affect the industry?)
- E – economic drivers (What are the prevalent economic drivers?)
- S – social drivers (e.g., How are consumer opinions changing?)
- T – technological drivers (e.g., Which technological innovations can affect the market structure?)
- L – legal drivers (e.g., Are there any current legislations regulating the industry, or can there be any change in the legislation for the industry?)
- E – environmental drivers (e.g., What are the environmental concerns for the industry?)

The division into these six categories is somewhat artificial and done for convenience because many drivers simultaneously have e.g., political, legal, and economic underpinnings. As described, the drivers and their influence were derived from the extensive interaction with project participants through interviews and workshops and from secondary sources. Sections 4.1–4.6 further present and describe the drivers.

This study uses the MICMAC method, which allows for fuzzifying the intensity of the relationship between two drivers based on experts' assessments [29]. Starting from a set of 30 drivers identified by experts in workshops and interviews (discussed in Section 4 and listed as variables in Appendix A), we develop the structural analysis to examine the relationships between drivers. First, we built the matrix of direct relationships (MDI, see Appendix B). In so doing, four researchers (coauthors of this study) engaged in a structured process of pairwise comparisons among the identified drivers. The four experts approached each relationship, variable by variable ($30 \times 30 - 30 = 870$ relationships), assessing the intensity of their perceived influence (using a scale of 0–3, or P for indicating potentiality). The evaluation took a few rounds where the experts evaluated the relationships independently, and after each round, a consensus matrix was reached based on a set of rules. The rules were such that if the majority (i.e., at least three experts out of four) identified a relationship or the lack of it, it was considered a consensus for each particular relationship. The average value was calculated for present relationships and 0 for the lack of relationship. For relationships where consensus was not reached, experts reconsidered their answers based on the assessment of the rest of the experts. During the final round, the relationships that did not reach consensus were discussed among the four experts, and a value was assigned for each of these relationships based on the discussion. After four rounds, the final matrix was built.

Next, using the MICMAC© software developed by LIPSOR (Laboratoire d'Investigation en Prospective, Stratégie et Organisation) for structural analysis, we classified the drivers in the consensus matrix based on their influence and dependence. Still, this step did not include the indirect relationships between variables. Therefore, we estimated the Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) using the above software to incorporate indirect and hidden relationships into the analysis, resulting in a matrix of Indirect Interdependencies (MII) [30] (see Appendix C for MII characteristics). This analysis shows the importance of each driver and allows us to identify specific drivers that play a significant role in the system through their indirect actions, which the direct classification did not reveal). The primary outcome accounts for the influence and dependence of each variable and can be represented on a plane where the x-axis corresponds to the dependence, and the y-axis corresponds to the influence. Thus, the drivers are clustered according to their functions in the system and based on their driving and dependent power [31], i.e., influential (***independent*** elements that are determinant or explanatory inputs and condition the system), relay (***linkage*** elements that are unstable by nature), independent (***autonomous*** or unconnected elements that can be excluded from the analysis), and ***dependent*** variables (output elements). This analysis is presented further in Section 5, with the implications of market drivers for future clean propulsion systems.

## 4. Drivers for the development of clean propulsion technologies

### 4.1. Political drivers

Unsurprisingly, political drivers emerged as strong determinants of the transition. The energy crisis has been further exacerbated after Russia's unprecedented attack on Ukraine in 2022, destabilizing the fossil fuel supply, especially in Europe. This destabilization affected the global prices for fossil fuels and facilitated the EU's overall motivation to wean off fossil fuels supplied by Russia and, in general, to increase fuel supply security.

Undoubtedly, a political will exists to reduce GHG emissions in shipping. Many initiatives have been under evaluation and consideration. For instance, establishing green shipping corridors is gaining traction, especially after the Clydebank Declaration was launched at COP26 in November 2021. Green corridors imply decarbonized maritime routes, including land-side infrastructure and vessels [32]. Hence, we include the following political drivers in our study: i) political will to reduce GHG emissions from shipping (POL1); ii) energy crisis (POL2); iii) green shipping corridors (POL3).

### 4.2. Economic drivers

While there is a clear pull in the marine transportation industry towards more sustainable operations, economic drivers are a determinant group that includes but goes beyond short- and mid-term considerations, e.g., the current increments in inflation and interest rates and their impact on investment decisions. Concerning the industry pull for clean sea transportation, initiatives such as the Sea Cargo Charter[1] and Cargo Owners for Zero-Emission Vessels[2] indicate a growing interest among the users and providers of maritime transport to eliminate emissions from sea shipping. Also, industrial customers' awareness of the life-cycle effects of products they purchase is growing. These customers require more significant volumes of and greater data detail, e.g., on life-cycle emissions of what they buy.

Fuel prices steer decisions related to utilizing carbon-neutral and zero-carbon fuels. However, fuel prices fluctuate heavily. Traditionally, prices of renewable fuels have been higher than those of fossil fuels, which is one reason for the slow change toward sustainable and alternative fuels. Still, the ongoing energy crisis will influence fossil fuel prices, which are difficult to predict. The price difference between fossil fuels and alternative fuels can become smaller.

Furthermore, sustainability principles are considered more profoundly in the finance sector, a trend known as green financing. For example, the EU taxonomy for environmentally sustainable economic activities and the Poseidon Principles are utilized by financial institutions to assess whether projects and investments to be financed contribute to sustainable development.

Finally, legal and normative aspects heavily influence markets. Market-based Measures (MBM) create economic incentives for reducing GHG emissions. For instance, IMO's Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 10) in October 2021 proposed the following market-based measures: a GHG levy, a cap-and-trade system, and a GHG fuel standard. The European Commission also proposed a basket of EU measures as part of the Fit for 55 package in the context of the Green Deal and started their implementation. The EU's Emissions Trading System (EU ETS) will be extended to cover $CO_2$ emissions from all large ships entering EU ports beginning from January 2024, and the 'FuelEU Maritime' Regulation aiming to increase demand and deployment of renewable alternative transport fuels will apply from January 2025. While these drivers can be categorized as legal, this section includes market-based measures because they will significantly impact the marine fuel, vessel, and shipping markets. Hence, we include the following economic drivers in our study: i) industry pull for clean sea transportation (ECON1); ii) industrial customers' awareness of life-cycle effects of products (ECON2); iii) green financing (ECON3); iv) the difference between fossil and alternative fuel prices (ECON4); v) taxation of emissions and unsustainable practices (ECON5).

### 4.3. Social drivers

Social drivers emerged as another relevant force directing the transition. Shifts in societal attitudes and behaviors primarily characterize these drivers. While they may not directly dictate industry decisions, they play a pivotal role in shaping the choices made by maritime stakeholders. Behavior changes among citizens have been slow but evident. Individuals have become more aware of sustainability and demand environmentally friendly goods and services, including transportation services, as a part of the supply chain for consumer goods. This shift in consumer preferences exerts pressure on transportation and shipping companies to adapt and provide carbon-neutral or zero-carbon transportation solutions. The impact of emissions, mainly local, on human health is receiving attention. Particle matter and pollutants like sulphur oxides emitted in near-shore areas harm human health. This heightened awareness has led to calls for reducing particle emissions. It has resulted in, for example, establishing Sulphur Emission Control Areas (SECA) in the Baltic and the North Seas.

Society is increasingly concerned about a clean environment. While social movements, such as Extinction Rebellion, aim to compel government action to avoid tipping points in the climate system, biodiversity loss, and the risk of social and ecological collapse, social media's role in driving green transition is undeniable. Regarding clean propulsion, social media discourses can affect the support for one innovation or another, which is then reflected in decision-making regarding propulsion on ships. The challenge that several workshop participants mentioned is that this support or obstruction can be based on emotions or wishful thinking rather than scientific facts about one technology or product's benefits and drawbacks. For example, nuclear power for ship propulsion has had a bad reputation, while several experts in this study claimed it might be a technically feasible solution for decarbonizing shipping. Finally, Environmental, Social, and Governance (ESG) reporting is becoming a standard tool for companies to communicate their efforts in environmental, social, and employee matters to investors, stakeholders, and society; the need to report on the environmental impact of economic activity creates broader awareness of the environmental impact of shipping, in particular. Hence, we include the following social drivers in our study: i) behavioral changes towards sustainable development (SOC1); ii) increasing concerns about human health impacts of shipping (SOC2); iii) increasing concerns about clean environment, social movements (SOC3); iv) ESG and company image (SOC4); v) discourse on green transition in social media (SOC5).

### 4.4. Technological drivers

It is commonly held that equipment technology is not a bottleneck for the green transition in shipping but the availability of alternative fuels [32]. Technology is also typically considered an enabler rather than a push element (like many digital technologies). Nevertheless, cost-efficient technologies may drive shipping markets in one direction or another.

Alternative fuels are considered the primary way to decrease shipping emissions because other measures, including operational measures, are insufficient to achieve policy goals [33]. Many options are available or under development (e.g., methanol, ammonia, and hydrogen), and technology is being developed to utilize these alternative fuels, along with infrastructure and other related aspects. The hydrogen economy, defined broadly as using hydrogen as an energy source, has been explicitly mentioned as an essential driver for the maritime propulsion sector. Hydrogen's advantages as an energy source include low or non-existent emissions.

Electrification, considered to have potential in shipping, especially in short-sea shipping, ferry operations, and inland waterway transportation, is happening in many transport industry segments. Further, combining batteries with other propulsion technologies to get optimal performance is a target in hybridization. Utilizing various power sources side by side is a likely scenario in many applications.

The variety of alternative fuel options and emerging alternative propulsion solutions creates high uncertainty regarding the 'fuel of the future' in the maritime sector. Given the need to develop refueling infrastructure for many fuels while simultaneously investing in vessels that will operate for decades, maritime actors face difficulties deciding which technologies to invest in. From a propulsion perspective, the

[1] https://www.seacargocharter.org/
[2] https://www.cozev.org/

current requirement seems to be "fuel flexibility," or the capacity to handle multiple fuels (or their blends) with the same system.

Digitalization and automation are considered important drivers in the maritime sector [34]. Route planning and automatized port queueing systems are examples of digitalization solutions influencing how ships perform regarding fuel efficiency and emissions. These systems can improve shipping's operational efficiency and reduce emissions per transport work. Automation on ships is increasing, and autonomous ships are being delivered yearly, albeit in small quantities. Removing crew from the vessels affects all ship systems, as vessels must be monitored and managed remotely, or those should operate independently based on autonomous systems. As MAN [14] argued, while the digitization trajectory is unlinked to decarbonization's progress, it can facilitate the latter, notably through new possibilities for control and optimization. We include the following technological drivers in our study: i) technological feasibility of carbon-free and carbon-neutral fuels (TECH1); ii) uncertainty regarding 'the fuel of the future' (TECH2); iii) hydrogen economy (TECH3); iv) electrification and hybridization (TECH4); v) digitalization and automation (TECH5).

### 4.5. Legal drivers

The IMO and EU have set net-zero targets for cutting GHG emissions from the shipping sector. There is a roadmap for adopting the regulations in the short- and mid-term. It can be expected that future regulations will be derived from these targets and the effect of the introduced measures on achieving the goals.

Current and upcoming requirements exist for ship design and performance regarding energy efficiency. The IMO introduced the Energy Efficiency Design Index (EEDI), which requires a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and size segments. The Energy Efficiency Existing Ship Index (EEXI), in turn, refers to the efficiency requirements for the existing vessels. Legal requirements to improve ships' energy performance include, e.g., a Ship Energy Efficiency Management Plan (SEEMP) and Carbon Intensity Indicator (CII). The latter sets requirements on $CO_2$ emissions per transport work, which should facilitate operational measures to reduce emissions.

As mentioned, a set of market-based measures is planned to promote the uptake of low-GHG fuels. FuelEU Maritime has been set to promote alternative low-GHG fuels in shipping. GHG energy intensity is required to improve by 2% in 2025 compared to 2020 and 75% by 2050. EU Energy Taxation Directive sets taxes for marine fuels. Then, starting in 2024, the EU's Emission Trading System (EU ETS) will be extended to cover $CO_2$ emissions from large ships entering EU ports.

Workshop participants have noted that while regulatory frameworks appear technology-neutral, they focus on tank-to-propeller emissions rather than the whole (fuel) life cycle, making some technologies (e.g., those relying on zero-carbon fuels) more compliant than those that perform well considering the life-cycle $CO_2$ emission (e.g., those dependent on biofuels). Current IMO regulations (EEDI, EEXI, CII) only address onboard tank-to-propeller $CO_2$ emissions. However, the IMO is working on guidelines to determine life-cycle $CO_2$ and GHG emission factors for all fuels, including biofuels and electrofuels, which should potentially increase their attractiveness as marine fuels compliant with the regulations. Nevertheless, GHG emission factors for biofuels and electrofuels heavily depend on assumptions about the production process. So, despite these efforts to consider the life-cycle perspective for alternative fuels, the uncertainty regarding the future compliance of carbon-containing fuels will likely remain.

Some regulations aim to increase the uptake of alternative marine fuels through the requirements for fuel infrastructure in ports. In particular, the EU's proposed Directive on Deployment of Alternative Fuels Infrastructure sets the minimum electric shoreside power supply by 2030. There is also a requirement set for passenger and container ships to connect to the shore power starting from 2030 for stays over two hours [35]. This directive also affects the development of LNG, ammonia, and hydrogen infrastructure.

Finally, developments in regulating battery manufacturing were also mentioned as potential drivers in the maritime sector. For example, the forthcoming European Battery Regulation provides guidelines for ensuring that batteries in the EU market are sustainable and safe throughout their life cycle. This can positively and negatively affect the proliferation of electric and hybrid vessels built in Europe. On the one hand, increased safety and sustainability of solutions developed in the EU can increase demand for such vessels. On the other hand, adhering to stringent sustainability and safety standards in battery production may result in increased costs, potentially leading to higher prices for electric and hybrid vessels. Hence, we include the following legal drivers in our study: i) IMO and EU targets for reducing GHG emissions in shipping (LEG1); ii) requirements for ship design in terms of energy efficiency (LEG2); iii) requirements for ship performance in terms of energy efficiency and emissions (LEG3); iv) Focus on tank-to-propeller emissions rather than life-cycle (LEG4); v) market-based measures to promote the uptake of alternative fuels (LEG5); vi) regulations concerning the sustainability of batteries (LEG6).

### 4.6. Environmental drivers

Naturally, our analysis shows a set of environmental drivers impacting the transition. Climate change is one of sustainable shipping's biggest drivers since global warming harms nature and people; finding ways to cut GHG emissions is essential. Human actions have caused problems for many species on the verge of extinction. Shipping impacts biodiversity in the sea, e.g., through biofouling and carrying invasive species or through collisions with marine life (e.g., whales), which explains why protecting biodiversity emerges as another important driver.

A certain consensus highlights drivers such as the concern about methane slip, noise, and natural resource depletion. First, methane slip is a drawback of utilizing methane and LNG as fuel. Methane is a potent greenhouse gas, about 28 times more powerful than $CO_2$ at contributing to global warming on a 100-year timescale and over 80 times more potent over 20 years [36]. Second, noise is an externality that has drawn increasingly more attention. The engines cause significant noise pollution that harms nature and species. Third, there are concerns about the availability of raw materials to enable the energy transition as rapidly as (European) policymakers envision, directing our attention to consumption and ways to reduce it.

Thus, experts call for a life-cycle perspective on different solutions. For instance, electric ships appear cleaner because they are emission-free where they operate, while vessels running on biofuels still have emissions, even if they are carbon-free from a life-cycle perspective. Organizations like Greenpeace ask about the life-cycle sustainability of batteries, while the industry has paid little attention to it. Considering the solutions' life-cycle impact (emissions), they appear to be becoming more prominent in regulation and among industry actors. Hence, we include the following environmental drivers in our study: i) climate change (ENV1); ii) biodiversity (ENV2); iii) methane slip (ENV3); iv) noise from shipping (ENV4); v) resource depletion (ENV5); vi) life-cycle and holistic perspective on different solutions (ENV6).

### 4.7. Analysis of interdependencies among the drivers

We used the MICMAC method described in Section 3.3 to analyze the interdependencies among the 30 PESTLE drivers presented in Sections 4.1–4.6 (also see Appendix A) and draw implications for future clean propulsion technologies regarding the most influential drivers.

As seen in Fig. 1, most of the drivers identified during the study can be considered ***linkage variables***, which means that these drivers are both influential for the entire system's direction and future and highly dependent on other variables in the system. Variables like political will to reduce GHG emissions from shipping (POL1), green financing

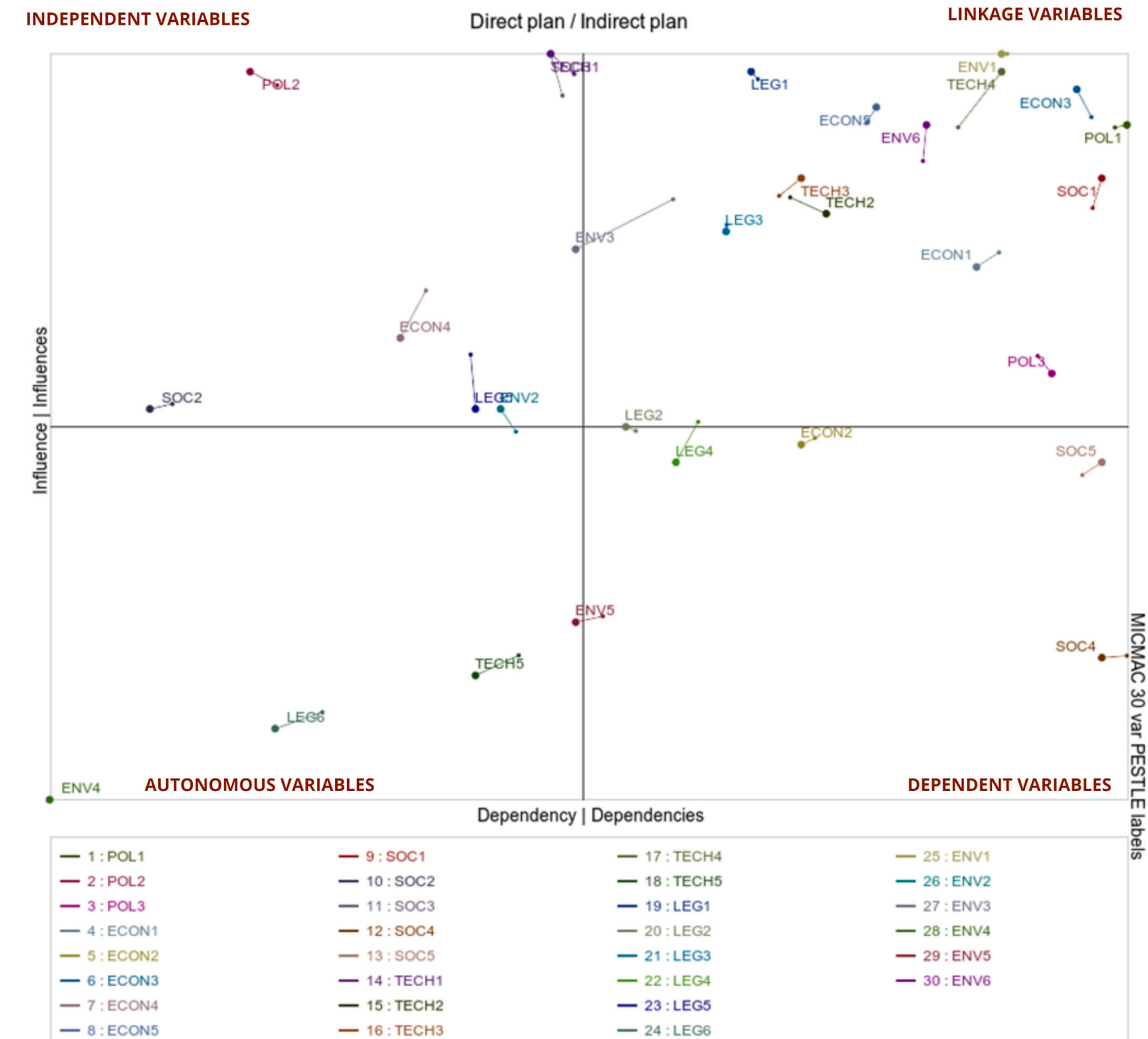


**Fig. 1.** Cluster diagram of the drivers for clean propulsion technologies, based on the analysis of direct (big dot) and indirect relationships (small dot) and displacements (line).

(ECON3), and behavioral changes toward sustainable development (SOC1) show a simultaneous strong influence and dependency. These drivers are relatively powerful in setting the direction for green transition in the maritime sector due to their impact on company and individual actions. At the same time, they depend on many other drivers regarding the direction and strength of their influence. For example, various legal drivers can affect future political will and green financing development. Uncertainty about 'the fuel of the future' (TECH2) is not surprisingly also a linkage variable, which can be interpreted as follows. While this uncertainty depends on many other variables such as new and upcoming regulations (LEG1–5), different technological developments (e.g., TECH1, TECH3, and TECH4), and economic drivers (e.g., current industrial customers' preferences for cleaner transport manifested in ECON 1 and ECON2 as well as ECON4), it also influences the green financing sector (ECON3), discourse on green transition (SOC5). It reciprocally affects legal and economic drivers regarding which technologies are promoted. Fostering coordination is necessary to maximize synergies and ensure that some drivers' development does not lead to unintended consequences in others and, therefore, to drive the shipping sector towards cleaner fuels and propulsion systems.Fig. 2.

Second, ***independent variables*** have a high influence on the system without being dependent on other drivers included in the scope of this analysis. Not surprisingly, the energy crisis (POL2) is the driver that significantly affects the development of clean propulsion within the maritime sector, also through affecting other factors such as the political will to reduce GHG emissions from shipping (POL1) but is relatively independent of any other drivers and is difficult to affect. Similarly, the difference between fossil and alternative fuel prices (ECON4) and market-based measures to promote the uptake of alternative fuels (LEG5) significantly influence the other drivers while remaining relatively independent. It must be noted that these three drivers (POL2, ECON4, LEG5) are interdependent, but they are still not easily influenced by the other identified drivers.

Third, discourse on green transition in social media (SOC5) and ESG

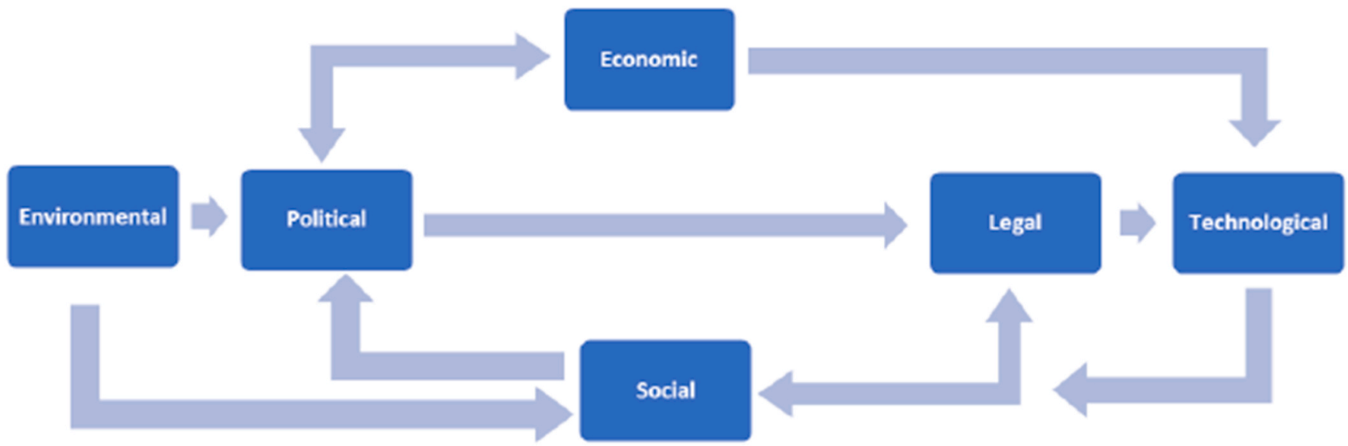


**Fig. 2.** The relationships among PESTLE drivers in the context of clean maritime propulsion.

and company image (SOC4) appear to be highly ***dependent*** on the multitude of identified drivers while not being highly influential on the direction of the development of clean propulsion technologies. It is, however, essential to understand what influences these drivers to minimize potential negative impacts.

Finally, ***autonomous drivers*** such as noise from shipping (ENV4), regulations concerning the sustainability of batteries (LEG6), and digitalization and automation (TECH5) are variables with low dependency and low influence. Such a result does not mean that they are insignificant or not necessary, but that currently, they are not seen as driving the change within the defined system. It is thus crucial to monitor the developments concerning these drivers for unexpected changes. The degree of their influence and dependence can also change over time. To provide an example, the concerns about noise from shipping can become more relevant if social awareness about the impacts of this externality increases, potentially followed by new stricter regulations on noise, leading to the need for technological developments to comply with these regulations.

Overall, the high share of linkage variables over other variable categories describes that the system is relatively complex and that there are a lot of interrelations between different drivers identified. In addition, it is essential to point out that several variables are located at the intersection of the clusters and thus have medium driving power and dependency.

## 5. Discussion

### *5.1. Implications of the drivers on the development of clean propulsion technologies*

Through analyzing the market drivers and discussions with project stakeholders, we derived several implications for the future development of clean propulsion technologies. Firstly, there is a clear focus on reducing $CO_2$ emissions, manifested in the maritime policy targets, regulations, pronounced societal concern regarding climate change, and the changing requirements toward climate neutrality of maritime transport from the customers. Any solutions, including those in the clean propulsion domain, can address these drivers. Although regulation aimed at reducing GHG emissions from shipping should be technology-neutral, several respondents in our study noted that 'zero-tailpipe emission' solutions, such as zero-carbon fuelled or electric vessels, are preferred. Such solutions are also more qualified to contribute to sustainable development, for example, when making investment or financing decisions.

Secondly, the high uncertainty regarding the prevalence of one alternative fuel or another in shipping creates difficulties for shipowners in choosing propulsion systems for new vessels or retrofitting existing ones. After reviewing multiple secondary sources and discussing with informants, we can conclude there are no clear winners among the future fuels. At the same time, some may be more or less feasible for different shipping sectors [33], but deciding which technology to bet on is impossible. The developments in alternative fuel technologies must also be reflected in developing corresponding engine solutions, onboard fuel storage systems, safety measures, etc. This means there is a need for significant research and development in multiple technological direction at once, and it is likely that there will be no one dominant technology that would replace the current socio-technical regimes based on ICEs that operate on fossil fuels. Moreover, propulsion systems should seemingly allow for certain flexibility in fuel use over the life cycle, including the possibility of vessels operating on fuel blends, on several fuels (as in dual fuel engines), and being retrofitted to operate on totally different fuels cost-efficiently. Although there are actors that have vested interests in maintaining the existing regime [37], for example, due to tied capital in prevailing propulsion technology, the uncertainty regarding future clean propulsion combined with a clear political and legislative push for reducing emissions from shipping appears to weaken the regime and create possibilities for multiple emerging technologies to enter ship propulsion sector.

In this respect, we can observe a more profound 'window of opportunity' created [22], where multiple niche technologies (alternative fuels, novel engine and propulsion concepts, vessel designs) are potential contenders for becoming a part of new socio-technical regime not dominated but one or two technologies. The transition, therefore, happens not only in terms of which technology will be the basis for clean propulsion in shipping, but also in the structure of the socio-technical regime to become more complex and based on multiple both competing and complementary technologies, which can together (and applied in specific shipping segments) fulfil the aim for net zero shipping.

### *5.2. The systemic interdependence of PESTLE drivers*

As the literature on sustainability transitions suggests, such changes are essentially systemic [38,39]. Hence, the drivers presented in this paper form a systemic whole. Following the PESTLE framework, this study discusses 30 drivers grouped into six clusters. Although all are individually relevant forces, the effects of these drivers cannot be considered in isolation, as many are synergistic and even contradictory and may lead the transition in different directions. Therefore, the big picture needs to evaluate their interrelationship (see Fig. 1).

Considering the types of drivers (following PESTLE) and based on the discussions with the study stakeholders, it appears that environmental forces are a primary driver that stimulates the industry and other stakeholders toward sustainable technologies, particularly when climate and health concerns increase. In essence, drivers like climate change can be attributed to the landscape level in the multi-level perspective. Environmental drivers and the consequent social movements pressure the policymakers to act accordingly, who must focus on making the socio-technical transition happen [40]. This is supported by the structural analysis presented in Section 4.7: social movements (SOC3) have a high driving power, as do concerns about health impacts of shipping (SOC2). Still, the process is not straightforward. Through discussions with the experts in the interviews, it is evident that social pressure drives the energy transition, and companies are developing new, greener technologies. End-users of the goods and products are more aware of the product's origin (ECON2) and are playing their part by putting pressure on them to make their products greener (ECON1), but their decisions are also influences by a number of factors, in particular political and technological.

However, the emergence of social movements is slow and calls for a shift in values and culture. As the process consolidates, green agendas emerge and become critical to cater to all these issues, playing an essential role in the socio-technical transition. Thus, political will (POL1) is one of the most vital forces in driving the socio-technical transition of the industry (as can be seen from).

Because of political will, new legislation may emerge since politicians want to gain or retain citizens' confidence. Politicians have direct links with rules and regulations, such as pushing forward specific technology or providing subsidies for adopting new technology. Organizations and institutions, such as IMO and the EU, have a central role in helping since they must promote technologically neutral regulations, as they have strived to do. Industry stakeholders' strategizing, investing, and decision-making aim to comply with the legislation. However, it means that the legislation must consider technological development, and if it does not reflect technological possibilities (e.g., treating new emerging technology in a non-neutral way), updating the legislation must be considered.

Moreover, the combination of legislative and economic drivers mediates the transition process, connecting political will and technological development. Legislation can introduce economic problems, such as increased fuel prices and operational costs. Shipping fleets using fossil fuels will face heavier taxation due to GHG emissions. With the evolution in inflation and interest rates, fuel and energy price volatility will also impact the shipping industry's transition. Our analysis shows that these drivers (ECON4 'The difference between fossil and alternative fuel prices' and LEG5 'Market-based measures to promote the uptake of alternative fuels') have the most influence on the green transition in this sector while being somewhat challenging to influence (see Section 4.7). Also, when stakeholders such as banks and financial institutions provide favorable conditions to shipowners and operators who choose lower emissions technologies and work towards decarbonizing the shipping industry (ECON3), it has a strong influence on the speed and direction of the development of clean propulsion in the maritime sector.

External pressure for technological developments is asserted by, for example, the green agenda of institutions such as the EU. Due to this pressure, technological solutions are being experimented with in the shipping industry [41], and uncertainties impact investment decisions. According to the data collected, developments can make the necessary adjustments to the existing combustion engines and the use of alternative fuels. These fuels can be used as single fuels, blended with fossil fuels (depending on their characteristics, e.g., whether they are used in liquid or gaseous aggregate state), or even utilized aside from other technologies such as electrification and battery technologies that can be used for running different systems of ships. With future technological development, alternative fuels can emerge as a dominant standard. They can replace the shipping industry's regime, resulting in its socio-technical transition. Moreover, as per the hybridization strategy explained by Geels [42] and Raven [43], once the technology is completely developed, combustion engines operating on fossil fuels can be replaced by engines that can only use alternative fuels or electrification. As discussed earlier, new technology may require legislation and social acceptance even after proven (reversing directionality).

In examining the dynamics of socio-technical systems, we adopt a perspective proposed by Geels and Schot [23] that views socio-technical regimes as complex 'dynamically stable' systems of heterogeneous elements, which are nevertheless interdependent. By employing the structural analysis method MICMAC, we identified the most influential drivers that affect the current regime in the field of maritime propulsion—considering clean propulsion technologies as niches provides insights for identifying and potentially creating 'windows of opportunities' [22] for the advancement of clean propulsion technologies within these niches.

One of the central conclusions drawn from our analysis is the pivotal role of closing the price gap between conventional and alternative marine fuels in facilitating the green transition within the maritime sector. Although actors in the maritime industry may not exert direct influence over these factors, the future development and adoption of clean propulsion technologies are undeniably tied to the cost dynamics of these 'fuels of the future.' This underlines the importance of policy and regulations in closing the price gap between conventional and alternative propulsion systems, considering the total cost of ownership (rather than only focusing on the fuel prices).

Our research offers a micro-level perspective on the transition as we explore the drivers identified by industry participants and their perception of the driving power. Thus, while many political, economic, and legal drivers refer to policy and regulations, their embeddedness within the broader system could be analysed. Furthermore, our analysis extends to the research at the strategic niche level to a structured examination of various drivers at the regime level. Fostering a deeper understanding of the drivers for developing clean propulsion in the maritime sector and their interplay can guide policymakers in developing targeted interventions. This, in turn, can catalyse the advancement of clean propulsion technologies, aligning with the overarching goal of sustainable maritime transportation.

## 6. Conclusions

### 6.1. Conceptual and managerial implications

In this paper, we uncover the complex transitory influence of many drivers on the development of the shipping sector towards zero emissions, grounded in the current situation in the maritime propulsion system sector. While much attention is given to the regulatory or legal drivers, which are admittedly the powerful drivers of change in the maritime sector, our study identifies other relevant drivers, such as the current technological base and industry pull for clean vessels from shipowners. The latter, in turn, is influenced by many drivers: regulations on vessel design, requirements set by financing institutions, concerns regarding the company image, and customer demand for clean transportation.

### 6.2. Marine policy implications

One of the key findings in this study is that while regulatory frameworks appear technology-neutral, many still focus on tank-to-propeller emissions rather than the whole (fuel) life cycle. This makes some technologies (e.g., those relying on zero-carbon fuels, such as hydrogen and ammonia) more compliant, albeit not explicitly, than those that perform well considering the life-cycle $CO_2$ emission (e.g., those fuels dependent on biomaterial or carbon, such as methanol, biomethane and bio- or renewable diesel). However, on the flip side, this brings unprecedented uncertainty regarding future fuel and propulsion technologies, and given the long lifetime of vessels, it leaves shipowners paralyzed when deciding to invest in one or propulsion technology. Thus, legislation and policy must consider the current development of different technologies to reduce GHG emissions from shipping to signal the options and to create a context of certainty that allows for better and faster investment decisions by the various actors in the ecosystem. For example, a unified life-cycle analysis methodology is in high demand (and under development by the IMO and the EU).

Further, a proper orchestration of the ecosystem regarding the availability of new fuels and respective technologies is necessary to ensure a primary degree of consensus. Such orchestration implies both coordinated intersectoral promotion of clean technologies, rather than only focusing on maritime sector, and the alignment of 'soft' and 'hard' governance as the role of social and economic drivers in the transition is indisputable. That is, we observed a few critical drivers for clean propulsion in the maritime sector, which are beyond the boundaries of the sector. Regulation and economic measures that aim only at the maritime sector are clearly not the only relevant political and legal drivers. Rather, the developments in the energy sector at large, digitalization, and electrification, to name a few, all affect in which direction the green transition will go.

While Kemp [44] argued that the typical compliance response to environmental policy and regulation is the use of expensive end-of-pipe solutions and incremental process changes offering limited environmental gain, we observe the opposite situation, where the simultaneous development of several alternatives to currently dominating propulsion based on fossil fuels creates high uncertainty in terms of future clean maritime propulsion. However, we still agree with Kemp [44] that 'policy instruments must be fine-tuned to the circumstances in which socio-technical change processes occur and tip the balance' to promote innovation. In the case of clean propulsion technologies, there is, in addition to rapid technological development on the system level and tightening regulations, a need for successful pilots and demonstrations of commercial feasibility by industry leaders. It is also reasonable to support R&D efforts related to multiple technologies at once and to facilitate collaboration among industry players for ensuring complementarity among propulsion technologies. This can ensure flexibility and adaptability while the regime is transforming.

### *6.3. Limitations and recommendations*

This study has certain limitations. Firstly, while the industry respondents are predominantly companies operating globally, and maritime shipping is international, there is a bias towards the European context. On the other hand, the regulations concerning clean shipping are most stringent in this area, which makes it a relevant geographic focus. However, it will be beneficial to expand the analysis of market drivers for clean propulsion technologies by studying other geographic areas where regulatory requirements are less stringent, and other drivers may come into play more pronouncedly. Secondly, while this study is done following the technology roadmapping approach, it is limited to the detailed presentation and analysis of market drivers. There is a need to analyse more detailed implications for the different technologies and solutions in the clean propulsion sector, accounting for the new technological developments.

## CRediT authorship contribution statement

**Tsvetkova Anastasia:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Hellström Magnus:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Schwartz Henry:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Rabetino Rodrigo:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Syed Hammad:** Writing – original draft, Formal analysis, Data curation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Part of the data is confidential to the research project or specific companies interviewed, while another part of the data (secondary) is publicly available.


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## Appendix A

Drivers for clean propulsion technologies in the maritime sector and the coding of corresponding variables in MICMAC analysis.

| Variable code name | Variable name |
|---|---|
| POL1 | Political will to reduce GHG emissions from shipping |
| POL2 | Energy crisis |
| POL3 | Green shipping corridors |
| ECON1 | Industry pull for clean sea transportation |
| ECON2 | Industrial customers' awareness of the life-cycle effects of products |
| ECON3 | Green financing |
| ECON4 | The difference between fossil and alternative fuel prices |
| ECON5 | Taxation of emissions and unsustainable practices |
| SOC1 | Behavioral changes toward sustainable development |
| SOC2 | Increasing concerns about human health impacts of shipping |
| SOC3 | Increasing concerns about clean environment, social movements |
| SOC4 | ESG and company image |
| SOC5 | Discourse on green transition in social media |
| TECH1 | Technological feasibility of carbon-free and carbon-neutral fuels |
| TECH2 | Uncertainty regarding 'the fuel of the future' |

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(*continued*)

| Variable code name | Variable name |
|---|---|
| TECH3 | Hydrogen economy |
| TECH4 | Electrification and hybridisation |
| TECH5 | Digitalisation and automation |
| LEG1 | IMO and EU targets for reducing GHG emissions in shipping |
| LEG2 | Requirements for ship design in terms of energy efficiency |
| LEG3 | Requirements for ship performance in terms of energy efficiency and emissions |
| LEG4 | Focus on tank-to-propeller emissions rather than life-cycle |
| LEG5 | Market-based measures to promote the uptake of alternative fuels |
| LEG6 | Regulations concerning the sustainability of batteries |
| ENV1 | Climate change |
| ENV2 | Biodiversity |
| ENV3 | Methane slip |
| ENV4 | Noise from shipping |
| ENV5 | Resource depletion |
| ENV6 | Life-cycle and holistic perspective on different solutions |

## Appendix B

Matrix of Direct Influences.

| POL1 | 0 | 1 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 2 | 0 | 1 | 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| POL2 | 3 | 0 | 2 | 1 | 1 | 3 | 3 | 2 | 3 | 1 | 2 | 3 | 3 | 2 | 3 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 0 | 0 | 2 | 2 |
| POL3 | 2 | 1 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 2 | 1 | 0 | 2 | 1 | 2 | 1 | 0 | 3 |
| ECON1 | 3 | 1 | 3 | 0 | 1 | 3 | 2 | 2 | 2 | 0 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 2 |
| ECON2 | 2 | 0 | 1 | 2 | 0 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 1 | 2 | 0 | 1 | 2 | 2 | 1 | 0 | 2 | 2 | 1 | 2 | 0 | 1 | 2 |
| ECON3 | 2 | 2 | 2 | 3 | 2 | 0 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| ECON4 | 3 | 2 | 3 | 3 | 0 | 2 | 0 | 3 | 2 | 1 | 1 | 0 | 1 | 2 | 3 | 3 | 2 | 2 | 2 | 0 | 3 | 3 | 3 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| ECON5 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 0 | 3 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 0 | 2 | 2 |
| SOC1 | 3 | 1 | 2 | 3 | 3 | 3 | 2 | 2 | 0 | 2 | 2 | 3 | 3 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 0 | 2 | 2 | 2 | 1 | 1 | 2 | 2 |
| SOC2 | 3 | 0 | 2 | 2 | 2 | 2 | 0 | 2 | 3 | 0 | 3 | 2 | 3 | 0 | 0 | 1 | 2 | 1 | 2 | 2 | 2 | 0 | 1 | 0 | 2 | 1 | 0 | 2 | 0 | 2 |
| SOC3 | 3 | 0 | 3 | 3 | 3 | 3 | 0 | 3 | 3 | 2 | 0 | 3 | 3 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 3 | 2 | 3 | 2 | 2 | 1 | 3 | 2 |
| SOC4 | 2 | 0 | 2 | 2 | 2 | 2 | 0 | 0 | 1 | 1 | 1 | 0 | 2 | 1 | 0 | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 1 | 1 | 1 | 1 |
| SOC5 | 3 | 0 | 1 | 2 | 2 | 1 | 0 | 1 | 2 | 2 | 2 | 3 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 0 | 2 | 2 |
| TECH1 | 2 | 3 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 0 | 0 | 2 | 2 | 0 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 2 | 3 | 1 | 2 | 1 | 2 | 2 | 2 | 3 |
| TECH2 | 0 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 3 | 3 | 0 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 0 | 2 | 0 | 2 | 2 |
| TECH3 | 3 | 2 | 3 | 2 | 2 | 2 | 3 | 0 | 2 | 0 | 0 | 3 | 3 | 3 | 2 | 0 | 3 | 2 | 2 | 1 | 0 | 2 | 2 | 0 | 2 | 2 | 2 | 1 | 3 | 3 |
| TECH4 | 2 | 3 | 2 | 2 | 0 | 2 | 2 | 3 | 3 | 0 | 0 | 3 | 3 | 2 | 2 | 2 | 0 | 3 | 2 | 2 | 2 | 2 | 0 | 3 | 3 | 2 | 3 | 3 | 3 | 2 |
| TECH5 | 2 | 0 | 1 | 2 | 0 | 1 | 0 | 1 | 2 | 0 | 0 | 2 | 2 | 2 | 0 | 0 | 1 | 0 | 1 | 2 | 2 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 1 | 1 |
| LEG1 | 3 | 2 | 3 | 3 | 2 | 2 | 2 | 3 | 3 | 0 | 2 | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 0 | 3 | 3 | 3 | 2 | 1 | 2 | 1 | 2 | 1 | 1 | 3 |
| LEG2 | 2 | 1 | 2 | 2 | 0 | 3 | 0 | 0 | 2 | 0 | 0 | 3 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 0 | 2 | 3 | 1 | 0 | 2 | 1 | 2 | 1 | 2 | 0 |
| LEG3 | 2 | 1 | 2 | 2 | 2 | 3 | 1 | 3 | 3 | 0 | 0 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 0 | 3 | 1 | 0 | 3 | 1 | 2 | 1 | 2 | 2 |
| LEG4 | 2 | 0 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 2 | 3 | 2 | 2 | 0 | 1 | 3 | 3 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 2 |
| LEG5 | 2 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 0 | 0 | 0 | 2 | 2 | 2 | 2 | 3 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 1 | 1 | 0 | 1 | 2 |
| LEG6 | 2 | 0 | 1 | 0 | 2 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| ENV1 | 3 | 2 | 2 | 3 | 2 | 3 | 0 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 1 | 3 | 2 | 3 | 2 | 2 | 2 | 0 | 2 | 3 | 0 | 2 | 2 |
| ENV2 | 3 | 0 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 3 | 3 | 3 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 2 | 3 | 0 | 0 | 2 | 2 | 2 |
| ENV3 | 3 | 0 | 2 | 2 | 2 | 2 | 0 | 3 | 2 | 0 | 3 | 2 | 2 | 2 | 3 | 2 | 2 | 0 | 2 | 2 | 2 | 3 | 2 | 0 | 3 | 2 | 0 | 0 | 0 | 3 |
| ENV4 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 1 | 0 | 2 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| ENV5 | 0 | 1 | 1 | 1 | 2 | 2 | 0 | 2 | 2 | 0 | 2 | 2 | 2 | 0 | 2 | 1 | 2 | 0 | 2 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 0 | 0 | 2 |
| ENV6 | 2 | 0 | 2 | 1 | 3 | 3 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 0 |

## Appendix C

Sums of rows and columns of MII.

| Variable code name | Variable name | Total of lines | Total of columns |
|---|---|---|---|
| POL1 | Political will to reduce GHG emissions from shipping | 137162 | 148734 |
| POL2 | Energy crisis | 142842 | 71247 |
| POL3 | Green shipping corridors | 106537 | 141578 |
| ECON1 | Industry pull for clean sea transportation | 120430 | 138000 |
| ECON2 | Industrial customers' awareness of the life-cycle effects of products | 95510 | 120983 |
| ECON3 | Green financing | 138576 | 146560 |
| ECON4 | The difference between fossil and alternative fuel prices | 115299 | 85004 |
| ECON5 | Taxation of emissions and unsustainable practices | 137894 | 125788 |
| SOC1 | Behavioral changes toward sustainable development | 126377 | 146670 |

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(*continued*)

| Variable code name | Variable name | Total of lines | Total of columns |
|---|---|---|---|
| SOC2 | Increasing concerns about human health impacts of shipping | 100096 | 61564 |
| SOC3 | Increasing concerns about clean environment, social movements | 141460 | 97641 |
| SOC4 | ESG and company image | 66316 | 149837 |
| SOC5 | Discourse on green transition in social media | 90561 | 145716 |
| TECH1 | Technological feasibility of carbon-free and carbon-neutral fuels | 144331 | 98713 |
| TECH2 | Uncertainty regarding 'the fuel of the future' | 127805 | 118697 |
| TECH3 | Hydrogen economy | 127999 | 117676 |
| TECH4 | Electrification and hybridisation | 137192 | 134226 |
| TECH5 | Digitalisation and automation | 66382 | 93585 |
| LEG1 | IMO and EU targets for reducing GHG emissions in shipping | 143642 | 115723 |
| LEG2 | Requirements for ship design in terms of energy efficiency | 96470 | 104414 |
| LEG3 | Requirements for ship performance in terms of energy efficiency and emissions | 124111 | 112816 |
| LEG4 | Focus on tank-to-propeller emissions rather than life-cycle | 97691 | 110179 |
| LEG5 | Market-based measures to promote the uptake of alternative fuels | 106722 | 89143 |
| LEG6 | Regulations concerning the sustainability of batteries | 58751 | 75431 |
| ENV1 | Climate change | 147050 | 138761 |
| ENV2 | Biodiversity | 96380 | 93326 |
| ENV3 | Methane slip | 127543 | 107865 |
| ENV4 | Noise from shipping | 47006 | 50201 |
| ENV5 | Resource depletion | 71613 | 101363 |
| ENV6 | Life-cycle and holistic perspective on different solutions | 132669 | 130976 |
| | TOTALS | 3372417 | 3372417 |

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