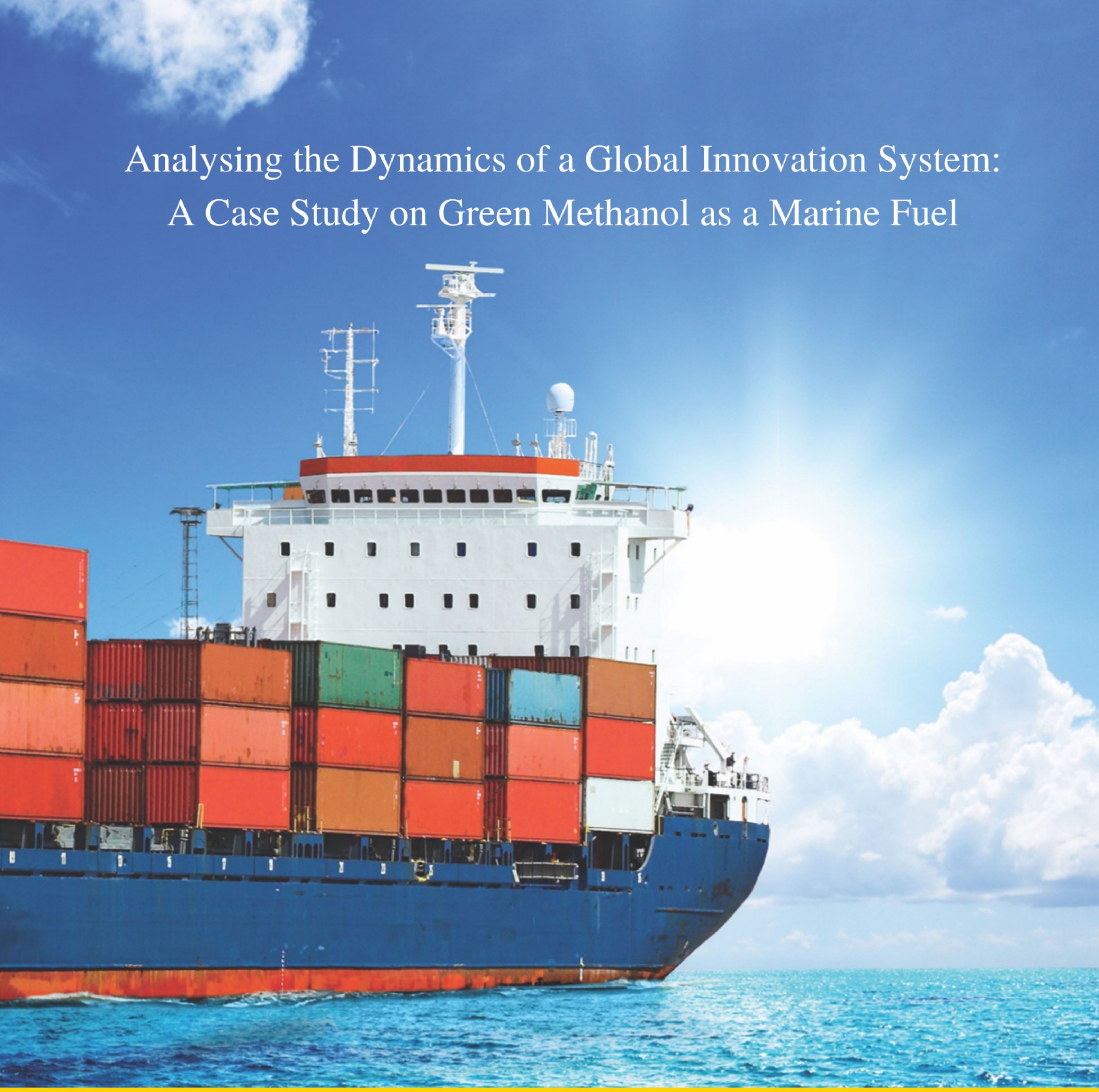
Analysing the Dynamics of a Global Innovation System: A Case Study on Green Methanol as a Marine Fuel



Master's Thesis

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Table of Contents

Glossary

Acronyms and Abbreviations

DUI	Doing Using Interacting
ECA	Emission Control Areas
EHA	Event History Analysis
EU	European Union
GHG	Greenhouse Gas
GIS	Global Innovation System
IMO	International Marine Organization
IS	Innovation System
NIS	National Innovation System
R&D	Research and Development
RIS	Regional Innovation System
SIS	Sectoral Innovation System
STI	Science and Technology-driven
TIS	Technological Innovation System

Abstract

Introduction

This research analyses the drivers and barriers to the global adoption of green methanol as a marine fuel, which is a fuel that offers a vital decarbonization solution to the maritime industry. The research builds on the Global Innovation Systems (GIS) theory since this theoretical framework showcases the essential activities needed for an innovation system to get to a more footloose adoption state.

Methods

Innovation systems thrive through stakeholders' pursuit of impactful events. To understand the prominent activities that occurred in the green methanol industry, an event history analysis was conducted. A global news analysis examined the temporal frequency of events and their correlation with the GIS resources. And in addition, semi-structured interviews with ten experts in the field enriched the understanding of the dynamics in the industry, leading to a robust dataset for a coherent narrative.

Results

The study presents a narrative that spans over five distinctive periods, illustrating the shifts in GIS maturation pathways and development barriers over time. The green methanol industry undergoes a transformative journey from a spatially sticky racing fuel in the United States to an innovative, globally recognized maritime fuel used to decarbonize the industry.

By focusing on the flaws in the innovation system, the research formulates a range of policy recommendations that are essential for the green fuel to become more widely mature. These recommendations hold the potential to upscale the adoption of the innovation and thereby mitigate emissions.

Discussion

While the research successfully achieved its objectives, it also highlights several areas for future investigation. Emphasizing that the parameters encompassed by the GIS theory do not fully capture the feedback loops of an innovation system. Additionally, it underscores the importance of thoughtfully selecting the event history analysis methodology, as outcomes may not always align with desired objectives. Moreover, the study suggests that future GIS studies can benefit from deconstructing the value chain of complex innovations, enabling a more comprehensive understanding of the different components influencing maturity within the system.

Conclusion

In conclusion, this research makes substantial contributions by its unparalleled scope, valuable policy recommendations, and insights into the flaws and prospective directions of GIS studies, firmly establishing its academic and social significance. Ultimately providing a solid foundation for policymakers and industry stakeholders in the green methanol sector to enhance their industry practices and facilitate further development of the fuel.

1. Introduction

The increasingly frequent and severe occurrences of extreme weather events show the urgent need for efficacious measures to safeguard the planet against the detrimental effects instigated by climate change (Ripple et al., 2022). Addressing the climate crisis requires collaborative efforts from academic, political, and grassroots entities. These stakeholders must join forces to develop the necessary scientific foundation and formulate strategies for achieving sustainable development (Adger et al., 2005; O'Neil, 2018; Elkington, 1998). Additionally, the discovery and maturing of new technologies that can enhance resource efficiency, mitigate environmental stress, and facilitate environmental restoration are as important (Hekkert et al., 2007).

Multiple authors have raised the question under what conditions such innovations emerge and thrive (Purkus et al., 2018). The authors discovered that solely relying on the narrow concept of market failures proved ineffective, leading them to broaden their perspective and encompass a range of system failures, including inadequately functioning networks and institutional defects. (Klein Woolthuis et al., 2005; Kuhlmann et al., 2010; Weber & Rohracher, 2012). So, the focus shifted to analyse the dynamic "system" where the innovation is settled in (Jacobsson & Johnson, 2000).

Such an "innovation system" (IS) can be defined as "a network of institutions in the public and private sectors whose activities and interactions initiate, import, modify, and diffuse new technologies" (Freeman, 1987, p. 1). The institutions mentioned are not only firms within the value chain but extend to universities, political networks, patent legislators, labor-regulating firms, opinion makers, and various other entities (Carlsson & Stankiewicz, 1991). To ensure the successful diffusion of an innovation, it is crucial that these institutions support each other (Dosi, 1988).

Carlsson and Stankiewicz (1991) pioneered the theorization of these supportive relationships for specific technological innovations, leading to the development of the "Technological Innovation Systems" (TIS) literature. Subsequently, authors identified the essential activities in a TIS and termed them the key "functions" necessary for the successful diffusion of an innovation (Hekkert et al., 2007; Bergek et al., 2008). Through an analysis of the strength of these functions, policymakers can identify system-building activities needed to facilitate the diffusion of an innovation, being particularly valuable when attempting to promote technologies that have an advantaging social impact (Wieczorek & Hekkert, 2012; Bergek et al., 2008).

The TIS theory is commended for its generalizability, as the functions apply to all technological innovations. However, debate revolves around placing spatial boundaries when analysing a TIS (Market et al., 2015). Placing regional or national boundaries raises concerns about short-sightedness and neglect of contextual factors (Coenen & Truffer, 2012). Focusing solely on a specific country or region may overlook contributions from foreign institutions (Binz et al., 2014; Gosens et al., 2015). Moreover, each country possesses unique sectoral, political, geographic, and technological contexts that shape the emergence of an IS (Bergek et al., 2015). Therefore, it is preferable to analyse the emergence of new technology without imposing spatial boundaries on the TIS (Binz et al., 2014).

Based on this non-spatially bounded concept, Binz and Truffer introduced the "Global Innovation System" (GIS) theory in 2017. The GIS theory recognizes that innovations are often formed and diffused by the collaboration of multiple spatially separated networks, each with its distinct context. Building on the TIS theory, the GIS theory identifies critical activities necessary for successful global diffusion of an innovation and connects these activities to four essential "resources": "Financial investment," "Knowledge," "Legitimacy," and "Market formation." Additionally, the GIS framework acknowledges that innovations can follow different maturation paths during their lifecycle. It categorizes these paths into a structured quadrant which is linked to the development of the resources.

IS theory is often employed as the theoretical basis when analysing the strengths and barriers that impact the maturation of an innovation. (Gruenhagen et al., 2022). Similarly, authors employ GIS theory to evaluate the resource strengths of widespread dominant innovations. However, it is crucial to note that these efforts have not yet attained a truly global focus. For instance, Heiberg and Truffer (2022) exclusively focused on the European Union, Rohe (2022) examined a specific region in Germany, and Hipp and Binz (2020) studied the maturity of innovation in two specific countries. Which is not peculiar since analysing an innovation on a genuinely global scale is acknowledged to be an “overwhelming task” (Binz & Truffer, 2017 p.22). Nonetheless, addressing this challenge is imperative to ensure that the IS concept aligns with our increasingly interconnected and globalized world (Weber & Truffer, 2017).

This research will thereby be novel since it evaluates the activities that support and hamper the success of an innovation at a truly global scale. Secondly, the research shows why and when an innovation shifts to a different spatial prominence and valuation. And thirdly, it aims to give international policy recommendations to eliminate systemic development failures. These three contributions address desired areas of future work associated with the GIS theory, highlighted by Binz and Truffer (2017).

This research focuses on the diffusion of green methanol, one of the most promising sustainable alternative marine fuel innovations for long-distance shipping (International Renewable Energy Agency, 2021). The intercontinental nature of the shipping industry accentuates the critical need for a widespread supply of this fuel to attain genuine success, thereby emphasizing the necessity of employing an innovation theory with a global focus to assess its viability.

Green methanol can play a significant role in achieving the plan of the international marine organization (IMO) to attain a 50% greenhouse gas (GHG) emission reduction by 2050 (Brynolf et al., 2014). Green methanol is derived through the synthesis of green hydrogen and captured carbon dioxide from industrial or geosources or through the gasification of biowaste products, such as municipal waste (Figure 1). Since this production method uses only renewable products, authors claim that the fuel can be produced and burned with almost 100% GHG reduction compared to conventional marine fuels (Lindstad et al., 2021). Which is essential since the maritime industry could be responsible for 10% of global GHG emissions by 2050 with its current growth (Verbeek, 2019).

Considering applicability, methanol is easily stored since it stays liquid at ambient temperature and pressure (Liu et al., 2019). Hence, minor infrastructure modifications are needed to provide methanol as a marine fuel compared to other alternative fuels (Andersson & Salazar, 2015; Svanberg, 2018; Netzer et al., 2015). Moreover, investment costs for the conversion of conventional vessels to methanol-fuelled vessels are estimated to be low in comparison to converting vessels to run on liquified natural gas (LNG) or Ammonia (McGill et al., 2013; Shi et al., 2023). Further, methanol spills biodegrade faster than traditional petroleum fuels (Winebrake, 2019). And methanol has already been successfully implemented in several marine trials (*SUMMETH*, 2017) and commercial projects (*Westfal-Larsen*, 2016; Lewenhaupt, 2015).

Despite the potential benefits of green methanol, the marine industry faces substantial obstacles that hinder the widespread adoption of this fuel (DNV, 2019). This is concerning since it may obstruct the pathway towards the decarbonization of the maritime industry. To seek which challenges have to be tackled, the GIS theory proves valuable as it enables a theoretic basis to identify the barriers that impede a successful GIS. By combining the GIS theory with the empirical case, the research question can be formulated as follows:

What are the drivers and barriers to the development of the green methanol marine fuel global innovation system?

An IS unfolds through a series of activities, enhancing or obstructing its trajectory toward maturity (Hekkert & Negro, 2009). Forming the basis to assess the drivers and barriers of the GIS by an event history analysis. This approach, initially developed by van de Ven et al. (1999) and previously applied in IS analyses by Negro et al. (2008) and Suurs (2009), examines the activities or "events" that have taken place within the IS. This examination is carried out through a news analysis, whereafter the events found are analysed to determine whether they have contributed to or hindered the resources of the GIS. Additionally, the methodology instructs that a narrative should be constructed that provides context and background information of the events. To gather this background information, semi-structured interviews are conducted with ten experts. Combining these datasets enables a detailed reconstruction of the events, strengths of the GIS resources, and network maturity levels, which collectively form a comprehensive basis to analyse the barriers to a widely adopted innovation. Furthermore, this approach allows the identification of weakened GIS resources, forming an encompassing basis for policy recommendations to enhance the development of the GIS.

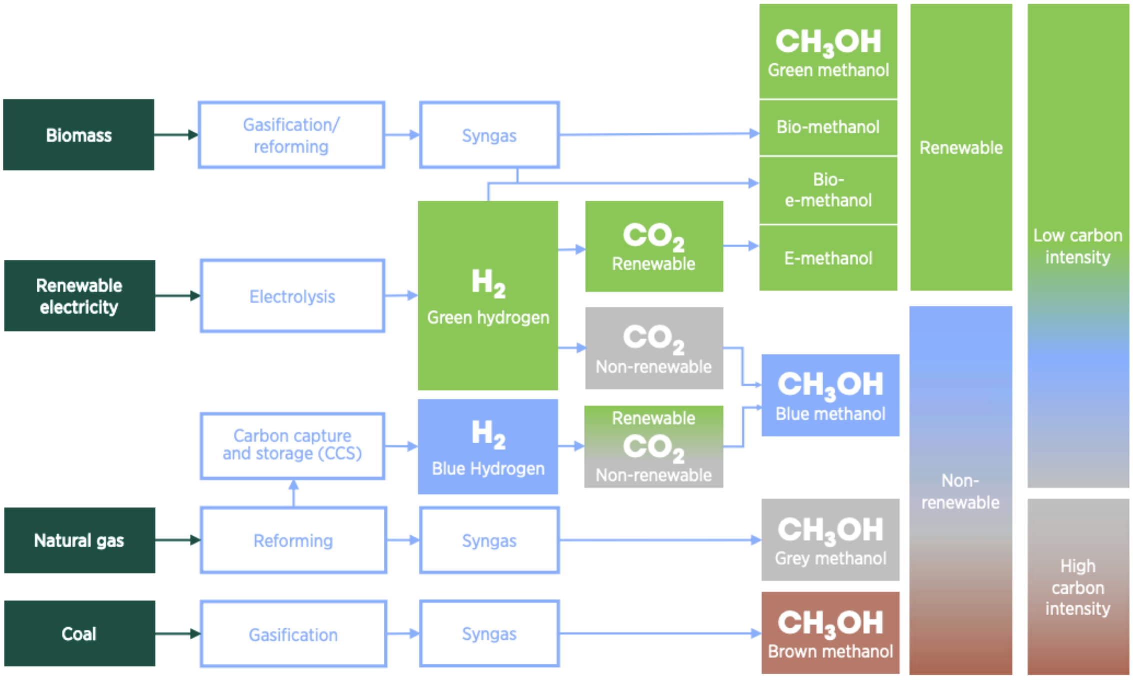


Figure 1, Methanol production pathways (International Renewable Energy Agency, 2021)

2. Theory

This research aims to analyse the strengths and weaknesses of the green methanol marine fuel GIS. The GIS theory proposed by Binz and Truffer (2017) is the leading theory used to understand the social phenomena around the maturing innovation. Before explaining the fundamental concepts of the GIS theory, the background of an IS, and, subsequently, a TIS are provided since these concepts form the basis of the GIS theory.

2.1 Innovation systems

In the 1950s, it was generally accepted that economic growth was attained by technological change (innovations) (Abramovitz, 1956; Solow, 1956). In the 50s, innovation was still seen as the result of linear development, starting with basic research, followed by applied R&D, and ending with production and diffusion (Brozen 1951; Maclaurin 1953). Eventually, this linear model was found to be invalid since an innovation's success showed to depend more on a firm's technological capabilities and the market's needs (Mowery & Rosenberg, 1978). Freeman (1982) and Kline and Rosenberg (1986) agreed and described that innovation had to be understood as an interactive process between numerous actors, with production, R&D, and market formation all running in parallel and reinforcing each other through positive feedback mechanisms. This holistic concept garnered commendation from numerous authors, leading Lundvall to introduce the term "system of innovation" in 1985. Since then, researchers have explored the emergence of Innovation Systems (ISs) with varying geographical and/or techno-economic scopes (Suurs, 2009).

"National innovation systems" (NIS) were conceptualized by Freeman (1988), Lundvall (1988), and Nelson (1988). NIS studies propose that the innovative performance of a nation relies on the interdependencies between policies and institutions (Fagerberg & Sapprasert, 2011). Thereby, this theory provides valuable insights for establishing more effective collaborations between policymakers and private entities at the national level (Nelson, 1988). Furthermore, the framework can help to elucidate why certain countries achieve greater success in realizing innovations and fostering economic growth compared to others (Freeman, 1987; Lundvall, 1992; Nelson, 1993).

"Regional innovation systems" (RIS) literature grew in the middle of the 1990s (Cooke et al., 1997; Malmberg & Maskell, 1997). RIS literature states that innovation networks on a small spatial scale would have notable advantages; lower costs for infrastructure, a build-up of skilled labour force, better transaction efficiency, and knowledge spillovers leading to more firm learning and innovation (Malmberg & Maskell, 1997). In the realm of RIS, Silicon Valley serves as a robust example. This region exhibits dense industrial networks, high knowledge intensity, effective government-business interactions, and ample venture capital, all of which strongly promote entrepreneurship and experimentation (Wonglimpiyarat, 2006).

Breschi and Malerba (1997) developed the concept of "sectoral systems of innovation" (SIS). The SIS framework was essentially a criticism of the NIS concept; "patterns of innovative activities differ systematically across technological classes but are remarkably similar across countries for each technological class" (Malerba & Orsenigo, 1996 p.47). A SIS focuses on a set of products for specific uses and a set of agents that carry out market and non-market interactions to create, produce, and sell products (Winter and Nelson, 1977).

Carlsson and Stankiewicz (1991) developed the concept of "technological systems of innovation." TIS analysis's principal starting point is not a geographical area or an industrial sector but a specific technology. The aim of TIS studies is to analyse the development of a particular technological innovation in terms of the structures and activities that support (or hamper) it. Thereby, the approach can be regarded as a micro-oriented variety of the SIS theory

(Hekkert et al., 2007; Markard and Truffer, 2008; Negro, 2007). The TIS framework is the basis for the GIS theory and will therefore be further explained.

2.2 The Technological Innovation System

According to Carlsson and Stankiewicz (1991), the TIS concept is defined as a "network(s) of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" (p. 111). The formation of a TIS involves three processes: entry of actors, formation of networks, and alignment of the institutional context (Bergek, 2008). These actors can be conceptualized as companies, government agencies, universities, intermediaries (e.g., industry associations and non-governmental organizations), and customers. Networks as industry alliances, technical committees, knowledge consortiums, and innovation networks. And the institutional context as the cognitive, regulative, and normative rules that enable and constrain actor behaviour (e.g., laws, technology regulations, routines, markets, culture) (Binz et al., 2016).

The TIS concept gives the base for one to compare the structure of several TISs statically and thereby explain the differences in performance. However, greater emphasis should be placed on the activities in the system since these truly contribute to the goal of the IS, which is the generation and diffusion of the innovation (Jacobsson & Bergek, 2004). Hekkert et al. (2007) proposed a set of essential activities or "functions" of ISs that actors should create to diffuse an innovation successfully. Seven functions were listed: "Entrepreneurial activities," "Knowledge creation," "Knowledge diffusion," "Guidance of the search," "Market formation," "Resource mobilization," and "Creation of legitimacy." Hekkert et al. (2007) further showed that these functions have feedback loops with three separable starting points in the system. Figure 2 depicts the seven functions and the three starting patterns labelled as "motors of change" (A, B & C).

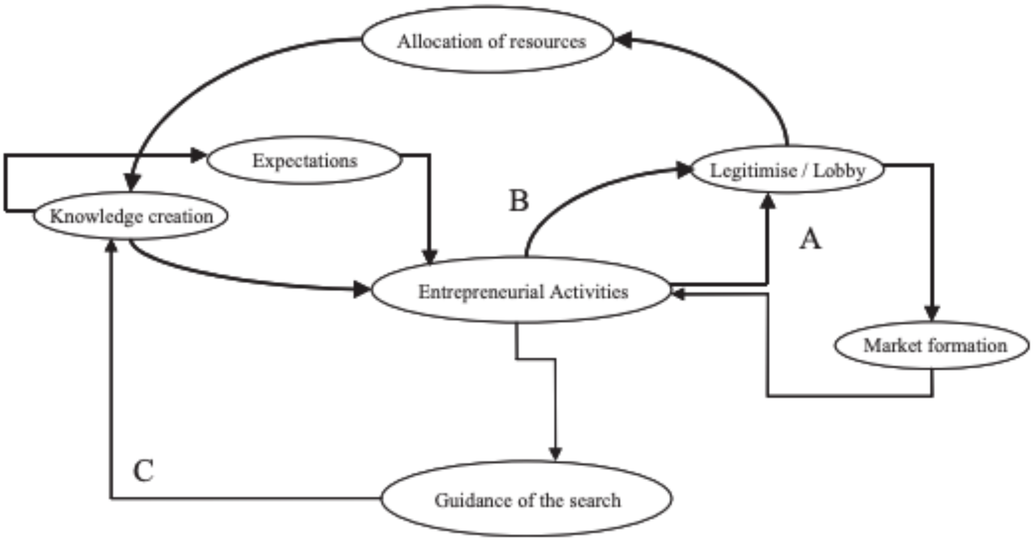


Fig. 2. Three typical motors of change.

Figure 2, The seven functions and the three motors of change proposed by Hekkert et al. (2007)

2.3 The Global Innovation System

The boundaries of the TIS in the globalized economy have become blurred and porous as never before; therefore, analysing them has become quite complex (Isaksen & Trippl, 2017). Binz and Truffer (2017) consent, however, state that the IS literature can still have a function if it attains more emphasis on linkages between regional and national innovation systems. Moreover, they emphasize that it is crucial to look at how the essential functions of an IS get spatially created and integrated. Such a perspective would be "instrumental for developing a more explanatory stance in the IS literature and developing policy interventions that reflect the increasing spatial complexity in the innovation process" (Binz & Truffer, 2017 p.1).

Binz and Truffer (2017) state that for a GIS to form, two spatial-specific processes are of essence: the creation of "subsystems" and the "structural coupling" of these subsystems. The creation of subsystems occurs through interactions among actors within networks or institutions operating at an urban, regional, or national scale (Binz et al., 2014). An example of a subsystem could be a local research facility that pays a diving school for updates on a coral culture project. However, a subsystem could also be more spatially extensive, for instance, an NGO pressuring a country's government to invest in coral reef conservation. For a GIS to thrive, it is crucial that these subsystems are successfully coupled. These structural couplings are essentially the foundation of an IS (Bergek et al., 2015). An example of a structural coupling could be the government funding the local research facility to investigate coral culturing (Figure 3).

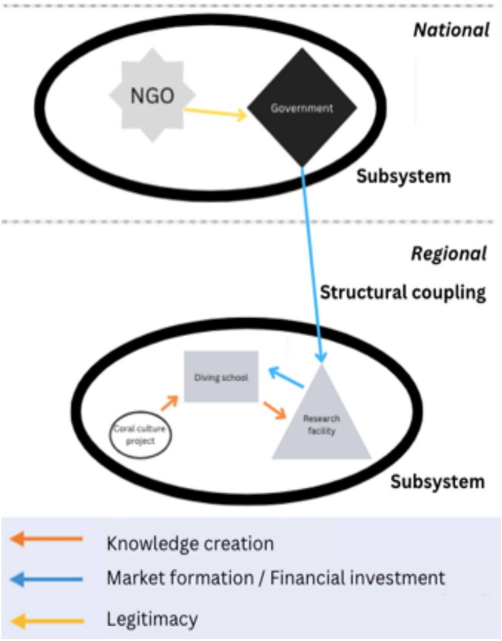


Figure 3, example of a simplified IS. With insights from Heiberg & Truffer (2022)

Recent literature has stated that the amount of these structural couplings would be enlarged by having different types of value chain segments in the IS (Rohe, 2020, Hipp & Binz, 2020), different abilities of actors to assimilate external knowledge (Binz & Anadon, 2018) and larger gaps of maturity between subsystems (Heiberg & Truffer, 2022). Moreover, organizations such as trade associations, NGOs, innovation platforms, and others that function between stakeholders (called "systemic intermediaries") should guide the GIS development since they can play a significant role in setting up the structural couplings between the different subsystems (Musiolik et al., 2020; van Welie et al., 2020).

2.4 The four essential resources for a successful GIS emergence

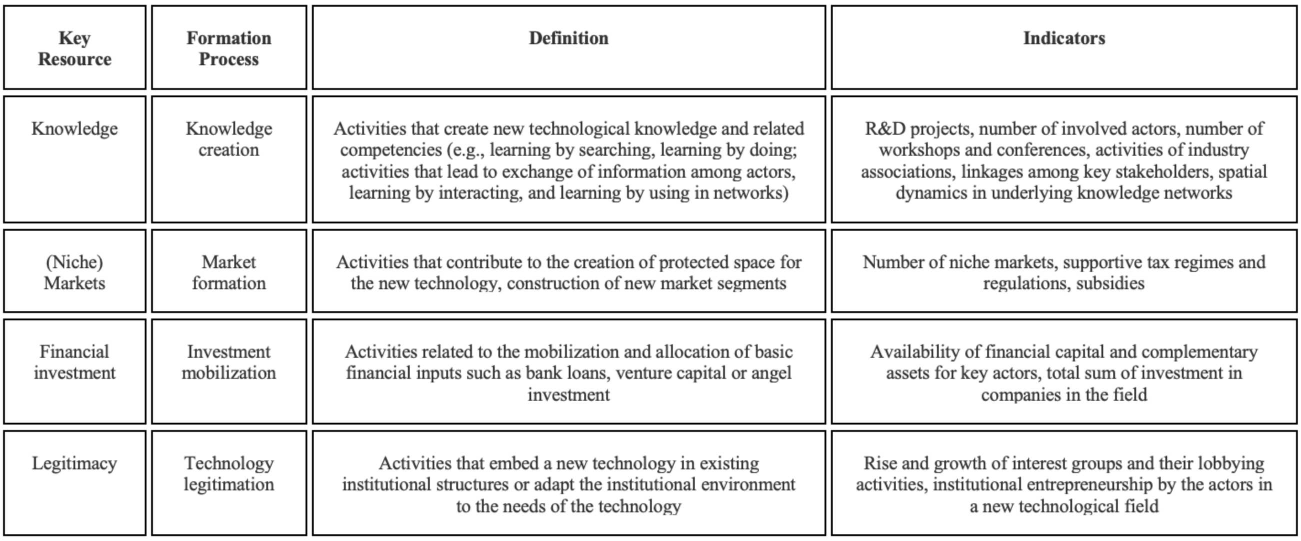
The structural couplings discussed are not only links between actors or subsystems; they truly fulfil a function that helps the innovation develop and diffuse. Binz et al. (2016) researched which functions would be essential in the formation processes of a GIS. Thereby the functions proposed in the TIS framework (see 2.2) were aggregated into four "resources": "Financial investment," "Knowledge," "Legitimacy," and "Market formation" (Table 1). These four resources can be understood as the pillars for the GIS to thrive; if any of them is deficient, the emerging industry will face a significant development barrier (Binz et al., 2016).

Knowledge creation is fundamental for every innovation development process (Bergek et al., 2008; Bathelt & Glückler, 2005). Knowledge can be both explicit and tacit, fulfilling as experienced-based know-how and network-based know-who (Binz et al., 2016).. Moreover, knowledge creation and recombination are essential for firms to sustain their competitiveness (Barney, 1991). Some forms of knowledge will be highly contextual and embedded in regional contexts, while others will be less sticky and easily transferrable. Events related to the knowledge creation resource are R&D projects, workshops, conferences, activities of industry associations, stakeholders linked to each other, and dynamics in knowledge networks (Binz et al., 2016).

Niche markets are market segments for new technologies and products that often do not pre-exist and must be created by actors themselves (Fligstein, 2007; Dewald & Truffer, 2011; Kemp et al., 1998). Market formation can be supported by governmental institutions creating for instance supportive tax regimes (Bergek et al., 2008; Hekkert et al., 2007). It is known that market-related structures especially play a decisive role in the long-term success of innovations (Dewald & Truffer, 2011). Events related to the market formation resource are the creation of niche markets, supportive tax regimes, supportive regulations, and supportive subsidies (Binz et al., 2016).

Financial investment is essential but often a scarce resource for actors in a new industrial field (Hekkert et al., 2007). Especially in the early industry formation phase, investment needs to be mobilized from various sources, e.g., angel investors, venture capital, commercial and investment banks, government organizations (Binz et al., 2016). Since the commercial potential of a new product is often uncertain, entrepreneurs will have to raise technology-specific expectations and thereby secure sustained investments in the emerging path (Hekkert et al., 2007; Bergek et al., 2008). Events related to the financial investment resource are available financial capital, complementary assets for key actors, and true investments (Binz et al., 2016).

Finally, the legitimacy resource underlines that the new industry and its products should align with the relevant institutional contexts (Aldrich & Fiol, 1994; Johnson et al., 2006). New products and processes not aligned with the normative and cognitive institutions will be confronted with scepticism and thereby a lack of user acceptance (Aldrich and Fiol, 1994). Therefore, it is vital to either adapt the innovation to existing institutional structures or adapt the structures to match the innovation's needs better (Bergek et al., 2008; Aldrich & Fiol, 1994). This can be done by promoting the suitable properties of the innovation (Johnson et al., 2006). Events related to the legitimacy resource are the rise of interest groups, lobbying activities, and institutional entrepreneurship.



Key Resource	**Formation Process**	**Definition**	**Indicators**
Knowledge	Knowledge creation	Activities that create new technological knowledge and related competencies (e.g., learning by searching, learning by doing; activities that lead to exchange of information among actors, learning by interacting, and learning by using in networks)	R&D projects, number of involved actors, number of workshops and conferences, activities of industry associations, linkages among key stakeholders, spatial dynamics in underlying knowledge networks
(Niche) Markets	Market formation	Activities that contribute to the creation of protected space for the new technology, construction of new market segments	Number of niche markets, supportive tax regimes and regulations, subsidies
Financial investment	Investment mobilization	Activities related to the mobilization and allocation of basic financial inputs such as bank loans, venture capital or angel investment	Availability of financial capital and complementary assets for key actors, total sum of investment in companies in the field
Legitimacy	Technology legitimation	Activities that embed a new technology in existing institutional structures or adapt the institutional environment to the needs of the technology	Rise and growth of interest groups and their lobbying activities, institutional entrepreneurship by the actors in a new technological field

Table 1, The four key resources, understood as necessary conditions for successful industry emergence (Binz et al., (2016)

2.5 Spatial development of innovations

Binz and Truffer (2017) saw that different innovations' subsystems and coherent structural couplings could be either very territorially embedded or contrarily spatially dispersed. So, the question was raised if it was possible to estimate how a GIS would spatially develop based on the technology and industry characteristics of the innovation. Thereby, two dimensions were conceptualised that form indicators for GIS's spatial development: the technological innovation dimension and the product valuation dimension.

The technological innovation dimension focuses on the knowledge resource. The dimension looks if industries gain knowledge by being either science and technology-driven (STI) or rely on learning by doing, using, and interacting (DUI) (Jensen et al., 2007). STI-based industries depend on knowledge that develops from analytical research that can be codified in models, patents, and reports. Examples of STI innovations are carbon capture, pharma, and bulk chemicals (Binz & Truffer, 2017). For these innovations to thrive, there is a need for knowledge exchange in internationalized networks (Asheim & Coenen, 2005; Martin & Moodysson, 2013). This industry type will therefore depend on knowledge spill overs beyond regional and national borders (Moodysson & Jonsson, 2007; Schmidt & Huenteler, 2016). So, the GIS of an STI will develop in a scattered international way. DUI industries are often engineering-based with a synthetic knowledge base; learning depends more on novel recombination of experience-based knowledge and competencies and not so much on scientific abstraction (Huenteler et al., 2016; Jensen et al., 2007; Martin & Moodysson, 2013). DUI innovations include early wind power, apparel, and furniture (Binz & Truffer, 2017). Given that these innovations arise from tacit knowledge and rely on face-to-face interaction, the GIS flourishes in spatial sticky environments (Martin & Moodysson, 2013; Schmidt & Huenteler, 2016). This implies that the development of the innovation will primarily take place within a regional or national context over a period of time (Binz & Truffer, 2017).

The product valuation dimension focuses on the other three resources: market formation, financial investment, and legitimacy. These three components can indicate how a technology becomes a valued product for a specific customer segment (Jeannerat & Kebir, 2016). The market formation resource indicates that innovations often depend on protected market niches, needing a socially accepted price-performance relationship and a good reputation aligning with pre-existing institutional structures (Dewald & Truffer, 2011; Fligstein, 2007). If these conditions suffice, this creates an attractive space for globalized investment (Coe & Yeung, 2015). The valuation of innovation can play out differently per product. Some innovations will be valuated homogenously ("footloose") since they have globally dominant designs and quality standards, e.g., consumer goods, mass-tourism, and electronics (Binz & Truffer, 2017). However, one could also imagine more complex or radical innovations dealing with niche market formation that need more effort to get social acceptance, e.g., nuclear energy, microbeer brewing, and luxury watches (Binz & Truffer, 2017).

To compare innovations, Binz and Truffer (2017) made a gradient with four generic GIS configurations based on the innovation and valuation characteristics (Figure 4). In Table 2 these configurations are explained; there it is shown how the resources from Binz et al. (2016) would develop if the innovation is present in such a configuration. It is important to note that the quadrant should not be utilized to precisely position innovations with numerical values, but rather illustrate the relative positioning of innovations in relation to one another.

It should be stated that many industries are characterized by complex combinations of DUI and STI-based learning and a mix of standardized and customized valuation (Stephan et al., 2017). Moreover, the position of an innovation in the quadrant is largely unstable and can make shifts when subject to the dynamics of the industry. The reasons behind radical shifts in GIS configurations remain still a significant research gap (Binz and Truffer, 2017).

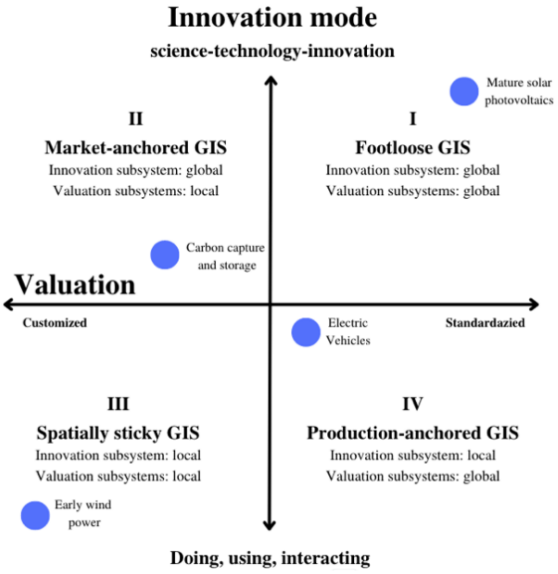
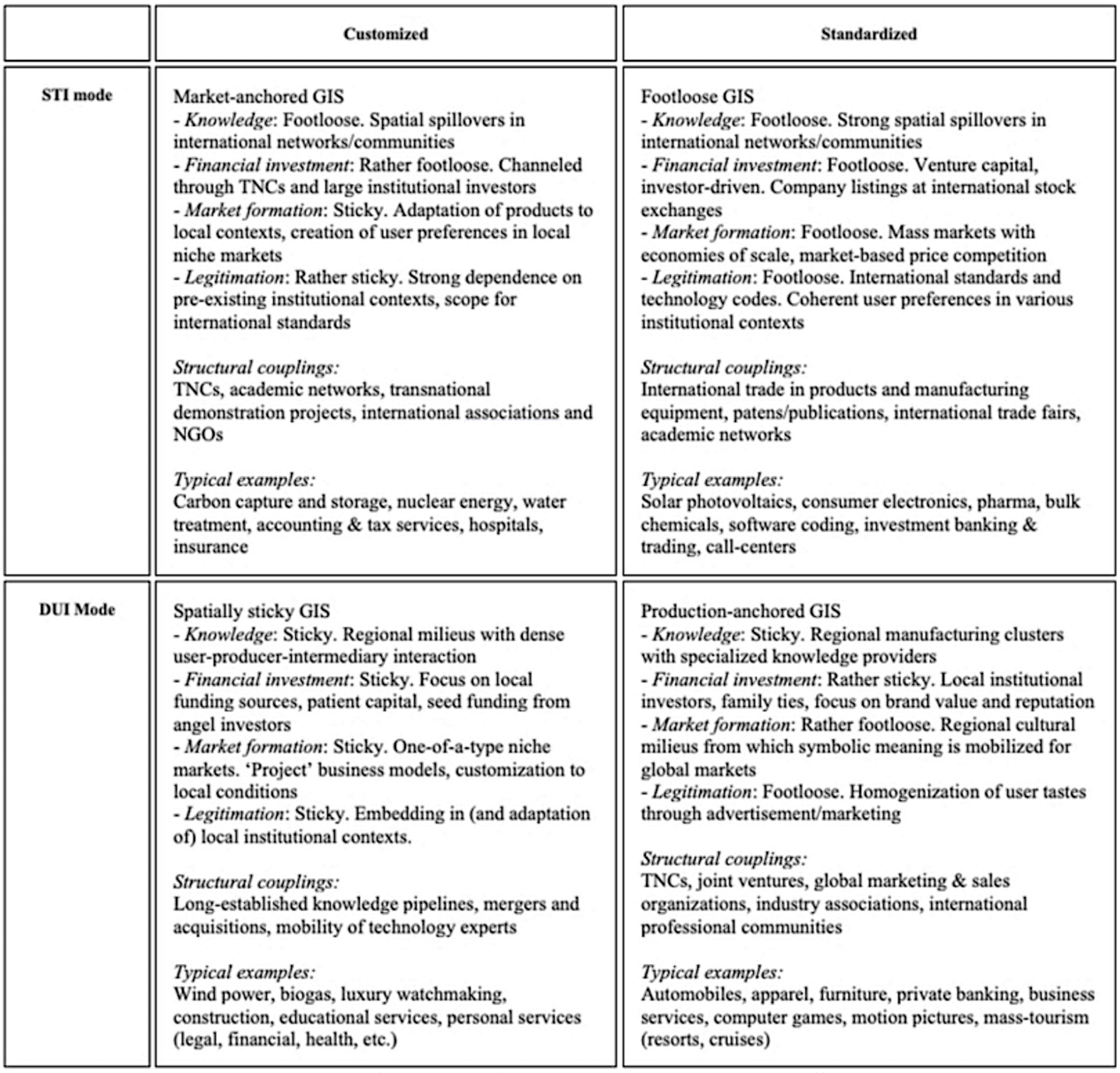


Figure 4, Gradient showing four GIS configurations based on the technological and product valuation dimensions proposed by Binz and Truffer (2017)



	Customized	**Standardized**
STI mode	Market-anchored GIS - *Knowledge*: Footloose. Spatial spillovers in international networks/communities - *Financial investment*: Rather footloose. Channeled through TNCs and large institutional investors - *Market formation*: Sticky. Adaptation of products to local contexts, creation of user preferences in local niche markets - *Legitimation*: Rather sticky. Strong dependence on pre-existing institutional contexts, scope for international standards *Structural couplings:* TNCs, academic networks, transnational demonstration projects, international associations and NGOs *Typical examples:* Carbon capture and storage, nuclear energy, water treatment, accounting & tax services, hospitals, insurance	Footloose GIS - *Knowledge*: Footloose. Strong spatial spillovers in international networks/communities - *Financial investment*: Footloose. Venture capital, investor-driven. Company listings at international stock exchanges - *Market formation*: Footloose. Mass markets with economies of scale, market-based price competition - *Legitimation*: Footloose. International standards and technology codes. Coherent user preferences in various institutional contexts *Structural couplings:* International trade in products and manufacturing equipment, patens/publications, international trade fairs, academic networks *Typical examples:* Solar photovoltaics, consumer electronics, pharma, bulk chemicals, software coding, investment banking & trading, call-centers
DUI Mode	Spatially sticky GIS - *Knowledge*: Sticky. Regional milieus with dense user-producer-intermediary interaction - *Financial investment*: Sticky. Focus on local funding sources, patient capital, seed funding from angel investors - *Market formation*: Sticky. One-of-a-type niche markets. 'Project' business models, customization to local conditions - *Legitimation*: Sticky. Embedding in (and adaptation of) local institutional contexts. *Structural couplings:* Long-established knowledge pipelines, mergers and acquisitions, mobility of technology experts *Typical examples:* Wind power, biogas, luxury watchmaking, construction, educational services, personal services (legal, financial, health, etc.)	Production-anchored GIS - *Knowledge*: Sticky. Regional manufacturing clusters with specialized knowledge providers - *Financial investment*: Rather sticky. Local institutional investors, family ties, focus on brand value and reputation - *Market formation*: Rather footloose. Regional cultural milieus from which symbolic meaning is mobilized for global markets - *Legitimation*: Footloose. Homogenization of user tastes through advertisement/marketing *Structural couplings:* TNCs, joint ventures, global marketing & sales organizations, industry associations, international professional communities *Typical examples:* Automobiles, apparel, furniture, private banking, business services, computer games, motion pictures, mass-tourism (resorts, cruises)

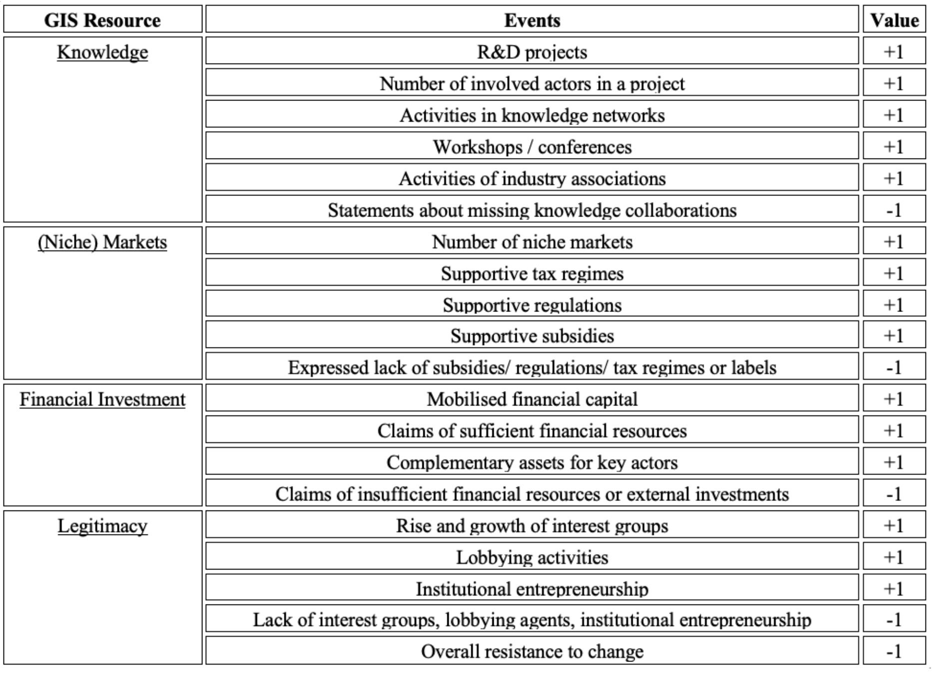
Table 2, Four configurations of a GIS proposed by Binz and Truffer (2017)

3. Methods

An IS can be seen as a sequence of interlinked socio-economic events resulting in shifts in the dominance of actors, institutions, and technologies. (Suurs, 2009). Making it imperative that the data used to assess the success of an IS takes into account these socio-economic events (Negro et al., 2008). Therefore, the decision was made to use an event history analysis methodology which was created by Van de Ven et al. (1999) and is still renowned in analyses that research the strengths and weaknesses of certain ISs (Ghazinoory et al., 2020; Hacking et al., 2019; Sadabadi et al., 2023)

To precisely define which events are of significance for an IS, Binz et al. (2016) developed a comprehensive list known as "indicators" that specifically enhance or hamper a certain resource (Table 3). These indicators are the only events under consideration in this research. The event history analysis method prescribes that the events serve as input data for two interrelated analyses: a quantitative trend pattern analysis and a qualitative reconstruction of the events by a comprehensive historical narrative (Suurs, 2009).

The starting point for both the quantitative and qualitative analysis is to construct a database with the events found by a news analysis (Step 1). Next, to create a better historical narrative, context information of the events is retrieved by semi-structured interviews with experts in the industry (Step 2). Then, to create the quantitative trend pattern, the number of events found in the database are positively or negatively linked to the four resources proposed by Binz et al. (2016) (Step 3). When this data is processed, certain "episodes" are distinguished by looking when the GIS experienced major development changes (Step 4). Then based on the qualitative and quantitative data, a historic narrative per episode is written, and a future vision of the GIS with policy recommendations for an enhanced diffusion of the innovation is made (Step 5).



GIS Resource	Events	Value
Knowledge	R&D projects	+1
	Number of involved actors in a project	+1
	Activities in knowledge networks	+1
	Workshops / conferences	+1
	Activities of industry associations	+1
	Statements about missing knowledge collaborations	-1
(Niche) Markets	Number of niche markets	+1
	Supportive tax regimes	+1
	Supportive regulations	+1
	Supportive subsidies	+1
	Expressed lack of subsidies/ regulations/ tax regimes or labels	-1
Financial Investment	Mobilised financial capital	+1
	Claims of sufficient financial resources	+1
	Complementary assets for key actors	+1
	Claims of insufficient financial resources or external investments	-1
Legitimacy	Rise and growth of interest groups	+1
	Lobbying activities	+1
	Institutional entrepreneurship	+1
	Lack of interest groups, lobbying agents, institutional entrepreneurship	-1
	Overall resistance to change	-1

Table 3, Classification scheme based on Binz et al., 2016 (inspired by Negro et al., 2008)

3.1 Data Collection

Step 1: News analysis

Nexis Uni, a comprehensive database containing complete articles from various international newspapers and magazines, was utilized to conduct a thorough search for events related to the GIS. To maximize coverage, two sets of search words were deployed (Table 4) and filtered for events relating to the resources (Table 3).

The first set of search words focused specifically on articles related to the production of green methanol for the fuel sector. The search criteria required articles to include the terms "e-methanol", or "renewable methanol", or "bio-methanol", or "biomethanol", or "bio-e-methanol", or "green methanol" in conjunction with "fuel". This initial search yielded 5,183 articles, from which 1,242 events were filtered.

Recognizing that the primary search did not retrieve all relevant events in the maritime industry, a secondary set of search words was employed. This secondary search targeted articles highlighting the utilization of methanol as a fuel source in the maritime sector. The search criteria required articles to include the terms "methanol-powered", or "powered by methanol", or "methanol-fuel(l)ed", or "fuel(l)ed by methanol", or "methanol motor" within the same paragraph as "ship", or "marine", or "maritime", or "freight", or "boat", or "barge" or "vessel". This secondary search resulted in 1,954 articles, from which 361 events were filtered.

The research investigated events spanning from 1981 (first relevant event) until 25/04/2023, ensuring a wide temporal scoped analysis. Each event discovered in the articles was documented in a coherent database with several inputs (shown in Table 5). In cases where multiple news articles centered around the same event, the event was coded only once in the database to avoid double counting. If the articles in Nexis Uni did not provide sufficient information to insert all necessary specifications, a general Google search was conducted to fill the gaps. However, events found passively through the Google search but not in Nexis Uni were not included in the database to ensure research replicability.

Key words	**Articles**	**Retrieved events**	**%**
methanol powered or powered by methanol or methanol fueled or fueled by methanol or methanol motor W/p ship or marine or maritime or freight or boat or barge or vessel	1954	361	18,47
e-methanol or renewable methanol or bio-methanol or biomethanol or bio-e-methanol or green methanol and fuel	5183	1242	23,96
Total	7137	1603	22,46

Table 4, Nexis Uni Search (1981 - 25/04/2023)

Description of the event	Date of the event	Location of the event	Institution(s) that initiated the event	Role of institution in the industry	Source	Search words used in Nexis Uni

Table 5, Database set-up

Step 2: Semi-structured interviews

To gain a comprehensive understanding of the events and obtain firsthand insights from industry insiders, a series of semi-structured interviews were conducted with ten key actors representing diverse areas of expertise in the GIS. For anonymity purposes, the interviewees are identified by acronyms; their profile information can be found in Appendix 7.1.

The interviews followed a scripted format that focused on gathering general information about specific events and exploring their influence on the GIS resources (see Appendix 7.2 for the interview script). While the interviews primarily centred around the events identified in the newspaper analysis, they also allowed for open conversations about other relevant developments brought up by the interviewees. In addition, the interviewees were encouraged to give their visions concerning the barriers that must be addressed to foster the maturation of the innovation.

The semi-structured interviews were recorded and transcribed, and the data was subsequently coded using NVIVO. The coding scheme was developed inductively to identify the most significant concepts and themes that emerged from the interviews.

3.2 Data analysis

Step 3: Linking events to GIS resources

In the database every event was coded to a resource as prescribed by the classification scheme (Table 3), which is a method inspired from Negro et al., 2008. The classification scheme indicates if the events enhance or hamper the diffusion of the innovation by + 1 and − 1. An example of an event that has a positive contribution to a resource is for instance, a conference about e-methanol which benefits Knowledge. An example of an event that hampers a resource would for instance be, an expression of lacking subsidies that would hamper Market formation.

Step 4: Distinguishing certain episodes

With the data collected, it is analyzed where the GIS has been situated and after which events the GIS made noteworthy shifts in the quadrant shown in Figure 4. The quadrant exemplifies different maturity stages underscoring different barriers and drivers a GIS can face (see section 2.5). An example of a shift in the quadrant could be the more footloose valuation of green methanol as a marine fuel after the IMO made more ambitious GHG reduction targets. Or a shift from DUI to STI after the test results of a methanol fueled ship are not only presented to a regional user of a ship but are picked up all around the world in transnational networks. After multiple of these noteworthy events showcase a shift in the quadrant a new period is demarcated in the results section.

To provide a better perception how these certain periods differ from each other, a world map illustrating the frequency of events by country, and a graphical representation of positive and negative events by resource are presented per period. Additionally, the overall shifts that occurred in the quadrant across all periods is graphically summarized at the conclusion of the results section.

Step 5: Writing down the narrative

By analyzing the quantitative and qualitative data, a narrative is formed to comprehend the GIS development over time. This narrative explores the influence of specific events on the diffusion of the innovation, considering resource creation, network maturity, and spatial aspects. Thereby, providing a detailed account of events that drive or hinder the success of the GIS. Moreover, the insights of the interviewees aid in identifying existing flaws of the GIS and serve as the basis for policy recommendations aimed at addressing these issues and promoting the maturation of the innovation.

4. Results Section

The analysis identified five distinct periods throughout the time, and tackles several policy recommendations, leaving the structure of the result section as:

1. The Predevelopment Phase
2. Development of Green Methanol Supply
3. A Low-Sulfur Maritime Industry
4. Contextual Factors Impede Commercial Progress
5. The Commercial Adopters Phase
6. Policy recommendations

4.1 The Predevelopment Phase (1981 – 2005) (Spatially sticky)

Throughout this period, the market for methanol as a fuel dominated the United States showcased by the numerous national events in Figure 5. This uptake was incentivized by the exceptional performance of methanol in racing engines (Miller, 1999). Consequently, leading to the adoption of the fuel in various American racing niches, including hydroplane- (Holcomb, 1989), Indy car- (Myers, 1990), and drag racing (Swayn, 1992), resulting in a significant number of events related to market formation, as evidenced in Figure 6.

The exceptional engine performance of methanol played a crucial role in its growing appeal. However, next to the fuel's performance, methanol combustion proved to be environmentally advantageous as well. It was found that compared to conventional car fuels, methanol generates fewer particulate matter, sulfur, and nitrogen emissions (Alper, 1988). This characteristic of methanol fuel offered a solution to the escalating environmental and health concerns associated with smog formation in urban centers in the U.S. during the 1980s (Reinhold, 1989).

The heightened environmental legitimacy prompted market formation by the U.S. government encouraging a wider adoption of the fuel. In 1988, the government introduced the Alternative Motor Fuels Act, which aimed to tackle smog in American cities, as documented by Barker (1988). As part of this initiative, subsidies were provided for research projects dedicated to the development of methanol-fueled buses, cars (Wald, 1989), and even the retrofit of a diesel train (Hidalgo, 1992). These efforts serve as tangible demonstrations of market formation aiming to give innovation a chance to address local challenges, underscoring the spatial stickiness of the GIS.

It is important to note that the excitement surrounding methanol primarily revolved around its brown and grey forms (made from coal and gas), thereby only predeveloping a potential offtake side for the green methanol industry. The U.S. did explore the production of methanol from biogenic sources, such as pig waste (Urell, 2003), municipal waste (Howard, 2005), and sugar (Schurr, 2005). However, most of these ventures remained in the realm of R&D as no true commercial-scale plants were established.

Regarding the knowledge resource, Japan became a national hub for R&D in the GIS. Kawasaki announced the development of methanol-fueled diesel engines for regular ships (Japan Economic Newswire, 1988), Toyota became the first automaker to export methanol-fueled cars to the U.S. (Snyder, 1989). And a Japanese research institute initiated a project to produce methanol from CO_2 and renewable energy, which can be considered the first e-methanol research project (Welna, 1992). However, significant wide-scale commercial products did not materialize.

Methanol did find an initial niche in the maritime industry, driven by the emergence of research on fuel cells during the 1990s. These fuel cells enabled to convert methanol into electricity, offering substantial efficiency improvements compared to traditional fuel combustion methods (Mossadiq, 1994). These cells were initially developed by a Canadian firm and deployed for auxiliary power in marine vessels in Germany, but the market for fuel cells gradually shifted their presence, eventually finding applications in portable batteries for phones and laptops (Kurzman, 2004).

While methanol as a fuel brought optimism, it also faced significant backlash and scrutiny. Concerns arose regarding the cost of methanol, potential toxicity associated with formaldehyde production, and safety risks posed by its invisible flames (Wald, 1989). These criticisms dampened the enthusiasm for methanol-fueled vehicles (Wood, 1989). Alternative fuel options, particularly ethanol made from corn, emerged as a more viable alternative, shifting attention away from methanol (U.S. Department of Energy, 2003), explaining the negative legitimacy events shown in Figure 6.

In summary, methanol fuel found many one-of-a-kind niche applications, particularly in the American racing industry. Additionally, its environmental legitimacy led the fuel to have government funded tests in anti-smog vehicle initiatives. However, most methanol projects remained at the research stage, with limited commercial adoption. Moreover, the emergence of ethanol as a more accessible alternative fuel shifted attention away from methanol, rendering its adoption spatially sticky in the U.S. The absence of methanol-fueled propulsion in vessels indicates that the innovation had not yet reached the early adopter’s stage. Nevertheless, methanol as a fuel gained initial experimentation and recognition, predeveloping the industry for wider applications.

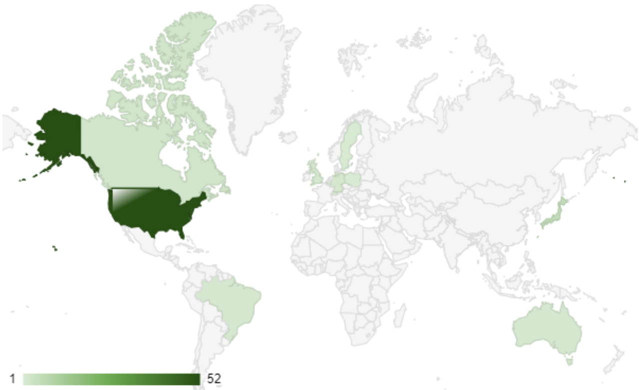


Figure 5, Events per country (1981 - 2005)

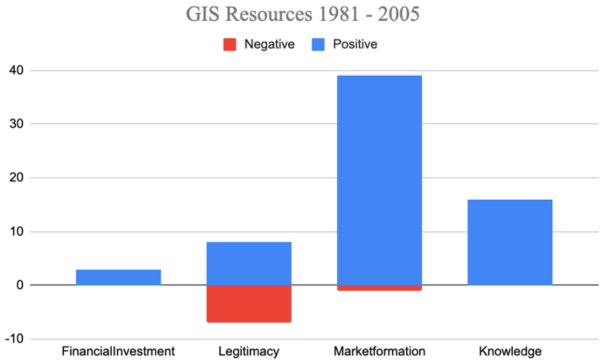


Figure 6, Resources of the GIS (1981 - 2005)

4.2 The Development of Green Methanol Supply (2006 – 2012) (Spatially Sticky)

During this period, the green methanol supply side matured due to the opening of commercial niche plants in the European continent. These plants garnered global legitimacy, being the most important factor behind the spatial expansion of events depicted in Figure 7.

The emergence of commercial biomethanol supply was pioneered by BioMCN, a company based in the Netherlands. In 2006, BioMCN took a significant step by transforming its mothballed grey methanol plant into a niche biomethanol facility that utilized glycerin as a feedstock (Wollerich, 2006). According to a former member of the methanol trade association,

> BioMCN was established to produce biomethanol in an existing methanol plant. When it started, there was no biomethanol available anywhere globally. So that was a very interesting period because they had to develop that market from scratch. They ultimately managed to do that fairly successfully, in the sense that they succeeded introducing some biomethanol as an additive to gasoline and supplying the energy production and chemical industry.

Another remarkable breakthrough on the supply side occurred in Iceland, where a company called CRI opened the first e-methanol plant. This plant utilized volcanic CO_2 and green hydrogen to produce methanol (Tran, 2010). This development showcased the potential of repurposing CO_2 as a valuable resource for fuel production. This innovative accomplishment garnered more footloose legitimacy; for instance, shortly after the opening of the plant in Iceland, a company in Australia expressed interest in acquiring the technology (Lambert, 2011).

The successes of these niche commercial green methanol plants caught the attention of governments as well. As this form of chemical production was widely recognized as a sustainable way to decrease dependence on oil imports (Marketwire, 2008). European countries saw this potential and took steps to form the market by offering substantial subsidies to green methanol plants. One of the examples is Sweden granting a subsidy of 45 million euros to support a biomethanol research plant (Lane, 2009). The concept of reducing the dependence of foreign oil through methanol was also embraced by the Chinese government. They actively funded trials that involved using 85% methanol fuel blends in cars as a means to create demand for their domestically produced grey methanol (Dolan, 2008).

These events showcase that methanol attained a more footloose legitimacy, picked up by governments trying to form their own market by subsidizing research projects, enhancing the number of events related to three resources (legitimacy, market formation, and knowledge). The market formation resource attained most events, as it encompassed both events relating to new niche plants and governmental incentives (Figure 8).

Despite the overall positive momentum around methanol during the 2000s, dissenting voices emerged as well. The Swiss Federal Environment Office (2007) questioned the overall sustainability of biomethanol, citing concerns about feedstock conversion efficiency and potential food shortages resulting from its biofeedstocks. And in 2009, Bruce Aitken, CEO of Methanex, the world's largest methanol producer and transporter, expressed concerns, stating, “A green plant would only be built a long way in the future,” as biomethanol production was deemed too costly. Explaining the negative events related to financial investment and legitimacy in Figure 8.

While many events within this period focused on assuring supply for applications in cars and the chemical industry, only one event focused on the maritime industry: the Scandinavian Effship Project. The Effship Project, funded by the EU, aimed to conduct research and identify fuels for vessels that could significantly reduce CO_2, NO_x, SO_x, and particulate matter emissions. A senior researcher involved in the research consortium stated that it was within this project that methanol was firstly recognized as a viable and promising alternative marine fuel.

In summary, the niche green methanol plants gained legitimacy by offering the ability to produce fuels independently of foreign oil feedstocks. This prompted governments to strengthen the market by providing substantial subsidies for plant development, and research focused on the fuel's applications. However, despite these advancements, significant progress was lacking in the maritime sector. No vessels with methanol-fueled propulsion were attained during this period, indicating a lack of R&D projects, regulations, and subsidies specific to the GIS. Its application in the marine sector thereby remained limited to a consideration in the Effship project. The GIS thus remained categorized as being spatially sticky.

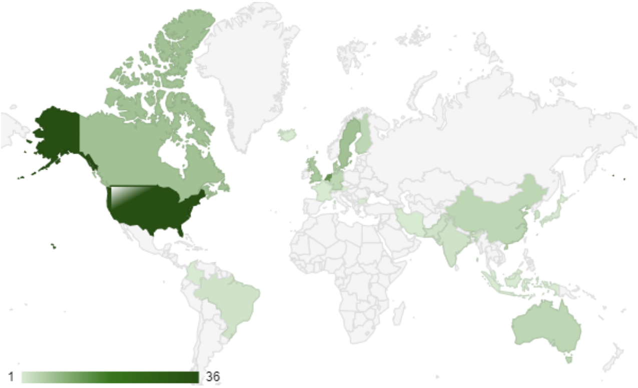


Figure 7, Events per country (2006 - 2012)

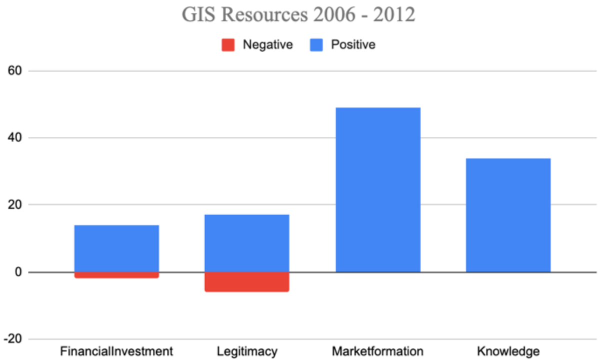


Figure 8, Resources of the GIS (2006 - 2012)

4.3 A Low-Sulfur Maritime Industry (2013 – 2015) (Spatially Sticky)

In this transformative period, market formation was the strongest driving force for the successes attained in the GIS. The most influential event was the establishment of the Emission Control Areas (ECA) by the IMO (2015) across Northern Europe and North America (see Appendix 7.3 for a map), leading to a significant surge of events in these regions, as depicted in Figure 9. In the ECA, the maximum permissible sulfur content in shipping fuel was reduced from 1.0% to 0.1% to combat air pollution

Stena Line, a Swedish ferry company, was actively searching for a way to comply with this novel regulation. They decided to collaborate with the Effship research consortium and embarked on the SpirEth research project in 2013, highlighting a strong user-producer research interaction (DUI). A senior researcher that was part of the SpiReth project stated,

> The SpirEth project aimed to find a low sulfur fuel for Stena before the 2015 regulations came into effect. Methanol seemed like an affordable option and thereby emerged as a viable alternative. Eventually, a dual-fuel engine that could either run on methanol or marine gas oil was successfully implemented in a vessel called the Stena Germanica in 2015.

While methanol proved to be a cost-effective fuel option at that time, it is crucial to acknowledge that the retrofit in the SpirEth project incurred significant expenses. A representative of a shipping company owning a methanol-fueled vessel emphasized,

> The SpirEth project was a government funded research project; I don't think Stena would have done it if they didn't get funding help because I think it was quite expensive. Despite the substantial investment costs, the potential benefits of being at the forefront of this technological innovation could have made it an appealing opportunity.

Showcasing that an event relating to the market formation resource (subsidy) truly enabled a pioneering event for the knowledge resource (R&D project).

Methanex, also saw the potential of using methanol as a fuel for their tankers. Leveraging their market position, Methanex pioneered a unique approach by establishing a niche in which their ships carrying methanol were equipped to fuel themselves using their own cargo. In a notable move forward, the company made significant financial investments by buying six methanol-fueled tankers in 2013 (Blenkey, 2013). A former member of the trade association stated,

> This decision not only proved to be economically advantageous for Methanex, as they could utilize their product as a cost-effective fuel, but it also served as a powerful showcase of the viability of their product as a marine fuel.

Although, these events could be recognized as a significant step towards more maturity in the GIS. It is important to emphasize that investments in the vessels during this period predominantly focused on utilizing brown/grey methanol, being far more economical than green methanol (CandM research, 2014). A representative of a methanol-fueled engine manufacturer noted, “Back then, CO_2 was not an issue. Nobody really talked about CO_2 in the same way we are talking today. SOx and NOx were the main problems because they were related to legislation which drove change.”

Moreover, rather than actively exploring alternative fuel options to comply with the ECA rules, most shipping companies installed scrubbers on their ships to effectively remove sulfur emissions. Which was regarded to be a more economical option and required fewer changes of a vessel highlighted by a former member of the methanol trade association. Thereby the usage of methanol gained criticism, shown by the negative financial investment and legitimacy events in Figure 10.

Global environmental consciousness did grow in this period leading to attention to greener transport in events like the 2015 Paris climate conference (Sirisena, 2015). As a result of this growing consciousness, the EU (2015) introduced the EU MRV (Monitoring, Reporting, and Verification) system that would commence from 2018 on, mandating ships to report their annual emissions. An EU Parliament member emphasized that this regulation would promote a transparent market where shipping companies can be held accountable for their environmental impacts.

In the car sector, the adoption of methanol as a fuel experienced a decline due to the growing interest in electric vehicles as a more prevalent and efficient solution. Electric vehicles offered advantages, including the elimination of efficiency losses associated with feedstock to fuel production (McKinsey&Company, 2014).

A lot of research projects were executed towards the feasibility and deployment of methanol fuel cells, showcasing the high level of knowledge-related events in Figure 10. However, as these events did not have any relevance for the maritime sector, they are not further highlighted. Further, no new green methanol plants were introduced in this period.

During this era, the enforcement of ECA regulations and favorable methanol prices played a crucial role in driving the first research project dedicated to the conversion of a methanol dual-fueled ferry. Moreover, a niche market was formed where a large methanol producer embraced its own product as a viable fuel option for its vessels. Despite these achievements, methanol as a marine fuel remained confined to a specific research project and a niche for methanol producers, signifying no widespread adoption and implementation of methanol as a marine fuel on a global scale. Moreover, almost all shipping companies chose scrubbers to comply with the regulations, thereby methanol did not gain a lot of widespread interest as shown in Figure 10. Therefore, the GIS still considered to be spatially sticky.

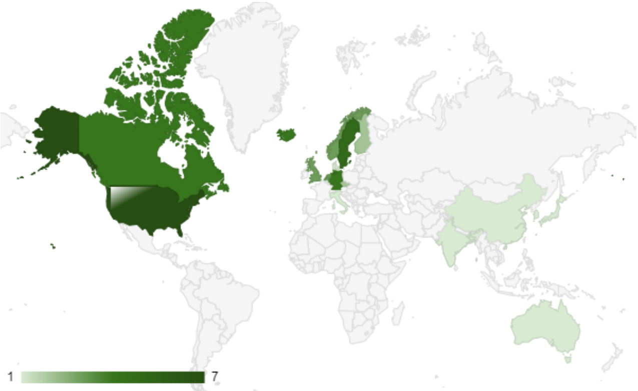


Figure 9, Events per country (2013 - 2015)

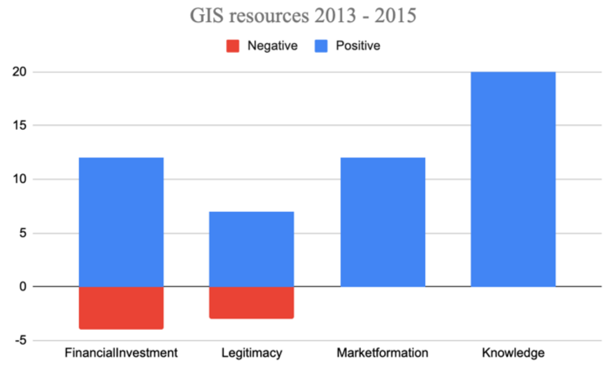


Figure 10, Resources of the GIS (2013 - 2015)

Figure 11, World's first methanol powered ship, the Stena Germanica launched in 2015 in Kiel Sweden (Portstrategy, 2015)

4.4 Contextual Factors Impede Commercial Progress (2016 -2020) (Spatially Sticky)

In response to the successful retrofit of the Stena Germanica, a methanol ship designer stated,

> After the conversion of the Stena Germanica, which I think everybody was happy with, methanol became more expensive than diesel oil. At first there were serious plans to convert numerous ships to methanol, but the raised cost difference ended these plans. So, methanol vessels would only be built if there were parties interested in its beneficial environmental aspects and could accept the higher fuel costs. This niche was found in government-funded shipping so, pilot service, road ferries, and passenger transport.

Indeed, few commercial investments were attained anymore due to a drop in the diesel price; the focus thus shifted to subsidized research projects in collaboration with governmental agencies, particularly in Scandinavian countries (explaining the dominance of events there in Figure 12). There were numerous research projects explaining the strong knowledge resource in Figure 13, with the most notable being: Summeth a project focused on designing ferries and coastal crafts to run on methanol, although a full-scale ship was never produced (Smith, 2018). The HyMethShip project researched the possibility of reforming methanol into hydrogen on a vessel, pre-combust it, capture and store the CO_2 on the ship, deliver the stored carbon to shore and synthesize it into methanol again creating a closed loop (Wermuth et al., 2018). And Greenpilot, which involved the conversion of a Swedish pilot boat into a methanol-powered vessel (Ramne, 2018). A ship designer stated that this Greenpilot project delivered essential knowledge: *"*Going from designing a big ship (Stena Germanica) to a smaller ship sounds easy. But there were a lot of challenges in this project since the safety measures were very strict compared to the true dangers in reality." Providing a barrier for further adoption of methanol on smaller vessels.

Next to the vessels designed for research purposes, the niche market for methanol producers who possessed methanol transport tankers did continue to grow; as a former representative of the trade association stated, *"*After Methanex ordered its ships, you also saw other methanol producers, particularly Proman, saying, *Okay, yes, interesting, we are going to let our future ships run on methanol as well.'*"

Methanol's effectiveness as a marine fuel had thus been successfully proven, thereby gaining more footloose legitimacy, but the high costs prohibited financial investments. A new niche market was found though, as orders came in for a vessel that was designed to be "methanol-ready" (Simons, 2017). The purpose behind constructing such a vessel was to install the required infrastructure for a dual-fuel methanol engine installation while excluding the engine itself. This would reduce the cost of potential retrofitting processes in the future if the price of methanol would become better.

However, the supply side picked up investments again in a footloose manner, with plans for biomethanol plants in Estonia (Olm, 2017) and Sweden (Gustavsson, 2017). But also, globally e-methanol plants attained investments in countries such as China (Lane, 2018), the Netherlands (Jacobsen, 2019), and Chile (Kaeser, 2019).

While these new plants represented certain progress, criticism was formed about their potential production capacity. In an article from DNV (2020), the CEO of the Methanol Institute stated, "Availability of methanol at scale is key. To be able to supply large fleets, we need more methanol to be produced. To capture 25-30% of the marine market, the production capacity supply would need to ramp up considerably."

Moreover, these plants did not always dedicate their production to the shipping industry but also aimed to provide other fuel markets. Methanol is namely a very important chemical building block, enabling it to end up in a ship in the form of methanol or be reformed to green diesel for a car or even end up in an airplane as sustainable kerosine (highlighted by DEC, TAS and ADV). Showcasing that there are many competitive sectors that can hamper the success of the GIS.

However, irrespective of the attainable supply of green fuels, international market formation initiatives were built that pushed shipping companies to look towards the decarbonization of their fleet. In 2018, the IMO implemented regulations aiming to reduce greenhouse gas emissions by 50% by 2050 (Schuitmaker & Pierpaolo, 2018). And the EU further bolstered environmental efforts in 2020 when the European Parliament announced plans to include the maritime sector in the EU Emissions Trading Scheme (ETS) from 2026 on. According to a member of the EU parliament,

> This inclusion requires that shipping companies pay for their pollution by attaining CO_2 emission credits. All ships operating within the EU have to account for 100% of their emissions, while ships coming or going to external regions have to pay for 50% of their emission output.

These efforts show that the market formation resource got more footloose in nature. However, some shipping companies, such as Maersk, X-press Feeders, and Hapag-Lloyd, displayed even greater ambition by actively lobbying for 100% decarbonization targets at the IMO by 2050. Showing that institutional entrepreneurs were standing up in the GIS, playing a larger role in the legitimacy of green fuels (Eckle, 2019).

These new rules and mounting environmental pressure triggered a surge of transnationally focused studies that aimed to determine the most feasible alternative fuel (methanol, LNG, ammonia, regular biodiesel, or hydrogen) that could decarbonize the maritime industry. These studies encompassed life cycle cost (LCC) and life cycle assessment (LCAS) for various ports and ships (Gibson, 2017; Owen, 2020). Highlighting the shift towards a more STI based knowledge resource.

While the implementation of regulations enhanced the market conditions for green methanol and its legitimacy grew in response to mounting environmental concerns, the utilization of methanol as a commercial fuel in shipping remained largely confined to a niche adoption market since commercial sailing on methanol beyond tanker ships of methanol producing companies was limited. Furthermore, the emergence of other fuels intensified competition and showed the need for continued research to determine the most efficient fuel option. The GIS thus remained spatially sticky as vessels were not widely adopted, although legitimacy and market formation became more footloose, and the knowledge resource got more STI-based.

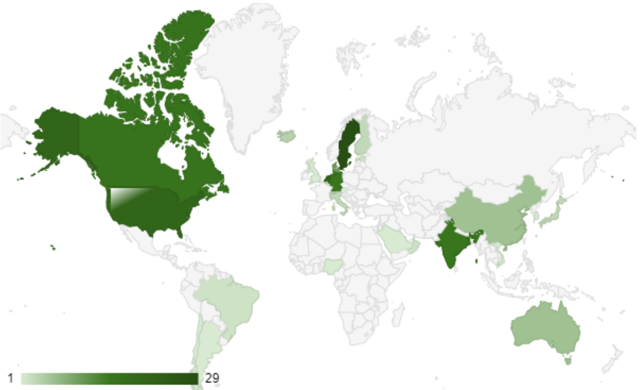


Figure 12, Events per country (2016 - 2020)

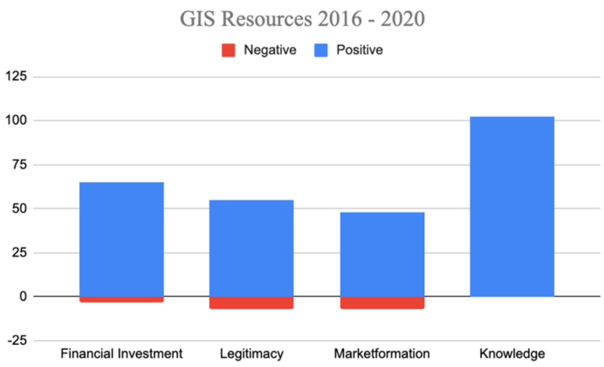


Figure 13, Resources of the GIS (2016 -2020)

4.5 The Commercial Adopters Phase (2021 - 25/04/2023) (Footloose)

The largest shift in the GIS quadrant occurred in this period, with all resources becoming footloose in nature. This is strengthened by Figure 15, showing events developing all around the world. The start of this shift commenced in 2021 with a decisive move by Maersk, one of the world's largest shipping companies. They placed an order for a methanol dual-fueled vessel, solidifying their commitment to decarbonize their fleet (Mandra, 2021). As the year unfolded, Maersk's dedication to decarbonize only grew stronger; by December, they not only raised their order to twelve methanol dual-fueled vessels but also announced that all their future new builds would be dual-fueled, actively striving for carbon neutrality (Northam, 2021).

While Maersk took a step by embracing methanol as a sustainable fuel option, the limited supply of green fuels in the market posed a significant challenge for many other shipowners to make investments towards methanol in 2021. A representative of Hapag Lloyd stated, “We do not yet know which climate-neutral fuels will be available in sufficient quantities in the future” (Aden, 2021). These concerns of attainable supply were shared by an interview with a representative of a company that owns a methanol-fueled ship*:* “We do not use green methanol constantly since there is not enough fuel available, and the supply is thereby very pricy”

However, Maersk demonstrated itself as an institutional entrepreneur in their pursuit to decarbonize the shipping industry. Morten Bo-Christiansen, the head of decarbonization at Maersk, passionately called for immediate action during an interview with The Guardian, “Rather than talking about how this can't be done, let's just get started and let's start scaling” (Stone, 2021). Recognizing the pressing supply challenge, Maersk demonstrated proactivity embarking on investments in methanol suppliers across the globe and lobbying governments to step into the e-methanol production market. They for instance-initiated dialogues with the governments of Spain (Buitendijk, 2022) and Egypt (Hamed, 2022), to promote the production and availability of this eco-friendly fuel.

The pressure to decarbonize economies became more prominent globally, leading governing bodies to make stronger footloose market formation commitments (Shaw-Smith, 2023). The EU emerged as a frontrunner in actively combatting GHG emissions, driven by its dissatisfaction with the IMO's target of a 50% reduction by 2050. In response, the EU introduced the FuelEU Maritime regulation, serving as a pivotal step towards a greener shipping industry. The regulation mandates an ambitious 75% reduction in CO_2 emissions by 2050, surpassing the IMO's target (PIW, 2021). As an EU parliament member stated,

> The EU's decision to take the lead in implementing such legislation stemmed from the lack of action at the IMO level, which left Europe with no choice but to act. However, the proposed law faced opposition who argued that it would impede the functioning of the liberal market and disrupt the current market positions of ports and shipping companies within the EU. Despite these concerns, the EU remained steadfast in its belief that it should lead the way in the clean transport sector. This target encourages the uptake of sustainable fuels; thereby the EU aims to drive innovation and scale, which will make these alternatives more affordable for all eventually.

Although, in 2023, the IMO did recognize the pressing environmental concerns and launched a more ambitious decarbonization strategy by implementing the Carbon Intensity indicator (CII) (Thurman, 2023). This indicator urges all vessels above 5000 gigatons to calculate their annual Carbon Intensity and demonstrate that it falls below a certain threshold to continue operating. A methanol-fueled ship designer commented,

> We now have the CII rule. Thereby, you have a benchmark that states what the carbon intensity of your ship should be before you can use it. And that means that if you have a ship that doesn't comply with the index, then you actually could end up in situations where your ship is not worth anything because you're not allowed to use it. Therefore, investing in the conversion to methanol, even though the operation is not necessarily cheaper, makes more sense.

Showcasing that the CII rule forms a global market with an incentive to adopt methanol as a fuel. However, there are loopholes in the rule, as highlighted by an advisor of the IMO,

> If you think about CII, it's not 100% accurate. Theoretically, you can lower your emissions by reducing speeds because that reduces the carbon intensity. But the environment doesn't care about carbon intensity; the environment cares about the absolute number of carbon emissions.

Next to the either effective or ineffective regulatory landscape, the growing pressure of clients urging shipping companies to decarbonize was also noted, as emphasized by Matt Stone, a partner at McKinsey, “There are very few boardrooms where the topic of decarbonization is not a top three topic of discussion today. The pressure is on for shipping companies to move more quickly in the climate transition” (Hawker, 2022).

Thereby tides began to shift towards more dominant footloose investments throughout 2022 and 2023 (Figure 14), with a remarkable surge in orders for methanol-fueled ships, as illustrated in Figure 16 showing that over 40 vessels were already ordered by April 2023. The true commercial potential of these vessels is signified by the fact that they were previously reliant on subsidies and are now manufactured without any governmental assistance, highlighted by ENG and DES.

Simultaneously, the supply side of the equation witnessed remarkable growth with investments in both bio- and e-methanol plants. This trend is clearly depicted in Figure 17, showcasing a substantial rise in the construction of both types of plants, with e-methanol plants leading the way. To shed light on the motivations driving the expansion of green methanol plants, an interview was conducted with a representative of a waste-to-methanol plant,

> We chose to produce methanol for two reasons. Firstly, it is, of course, a versatile product that can be used in various sectors, such as shipping, road transport, and potentially aviation in the future. Secondly, the offset market for this product is so large there is even more demand than we can currently meet.

However, it should be stated that Ammonia, LNG, and biodiesel also emerged as promising alternative fuel options with decarbonizing potential (Kristiansen, 2023; Miller, 2023; Taylor, 2023), prompting some shipping companies to embrace these fuels or leave them indecisive due to the absence of a definitive alternative fuel “winner” (Marriott, 2022).

Furthermore, R&D was still actively conducted and targeted to identify new feedstocks to produce methanol. In 2022, research projects were done aimed to utilize CO_2 obtained through direct air capture (DAC) to produce methanol (Reynolds, 2022). This method gained significant attention and was favored by a researcher involved in critical assessments of using methanol as marine fuel,

> Our research institute strongly supports the broad implementation and advancement of DAC as a pragmatic and effective approach to address CO_2 emissions. Although it is acknowledged that industrial point sources and biogenic sources exist as alternatives, it

is important to recognize their limitations in terms of availability. Additionally, reliance on these sources introduces the inherent risk of entrenching a continued reliance on carbon-intensive industries.

However, it is important to note that this technology comes with significant costs (Shayegh et al., 2021).

The GIS has developed towards a more footloose state over the five periods mentioned (Figure 18). This period was the first where a majority of events revolved around investments, mostly from methanol-fueled vessel orders and established methanol plants. This showcases a tangible commercial adoption of the GIS. Moreover, a significant portion of events were focused on conferences and activities organized by industry associations showing that knowledge was more shared in international contexts (footloose), and fewer true research projects were executed. Also, global environmental concerns and regulatory requirements helped to gain widespread legitimacy for green methanol. Thereby all GIS resources got in a more footloose state. Although, despite the substantial number of orders for methanol ships and green methanol plants, the market has not reached full maturity yet as these vessels and facilities are mostly still to be constructed. Which signifies that the full effects of the green methanol maritime fuel industry are still to be understood.

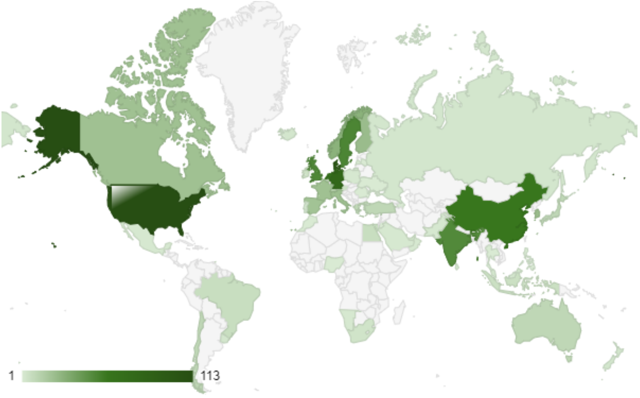


Figure 14, Events per country (2021 – 25/04/2023)

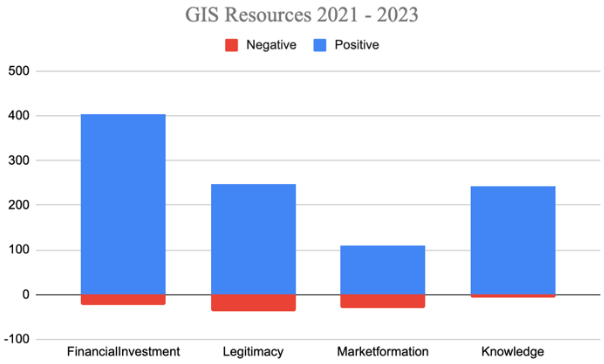


Figure 15, Resources of the GIS (2021 – 25/04/2023)

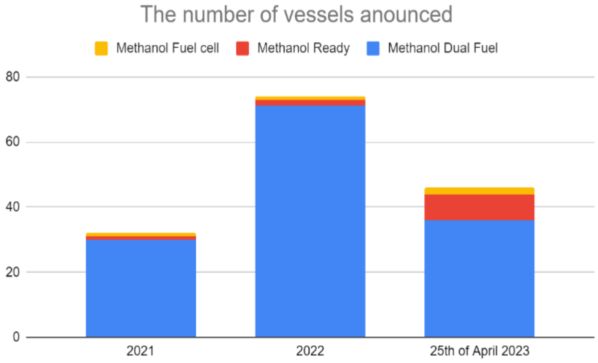


Figure 16, Vessels ordered (2021 – 25/04/2023)

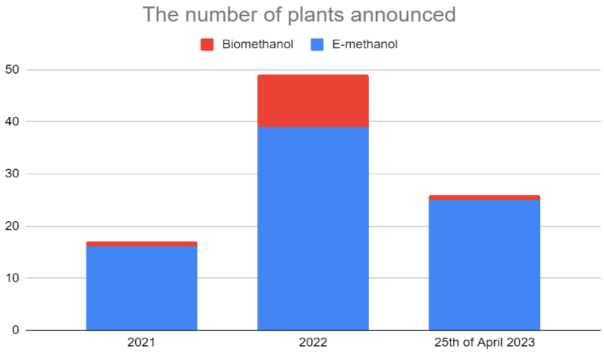


Figure 17, Methanol plants built (2021 – 25/04/2023)

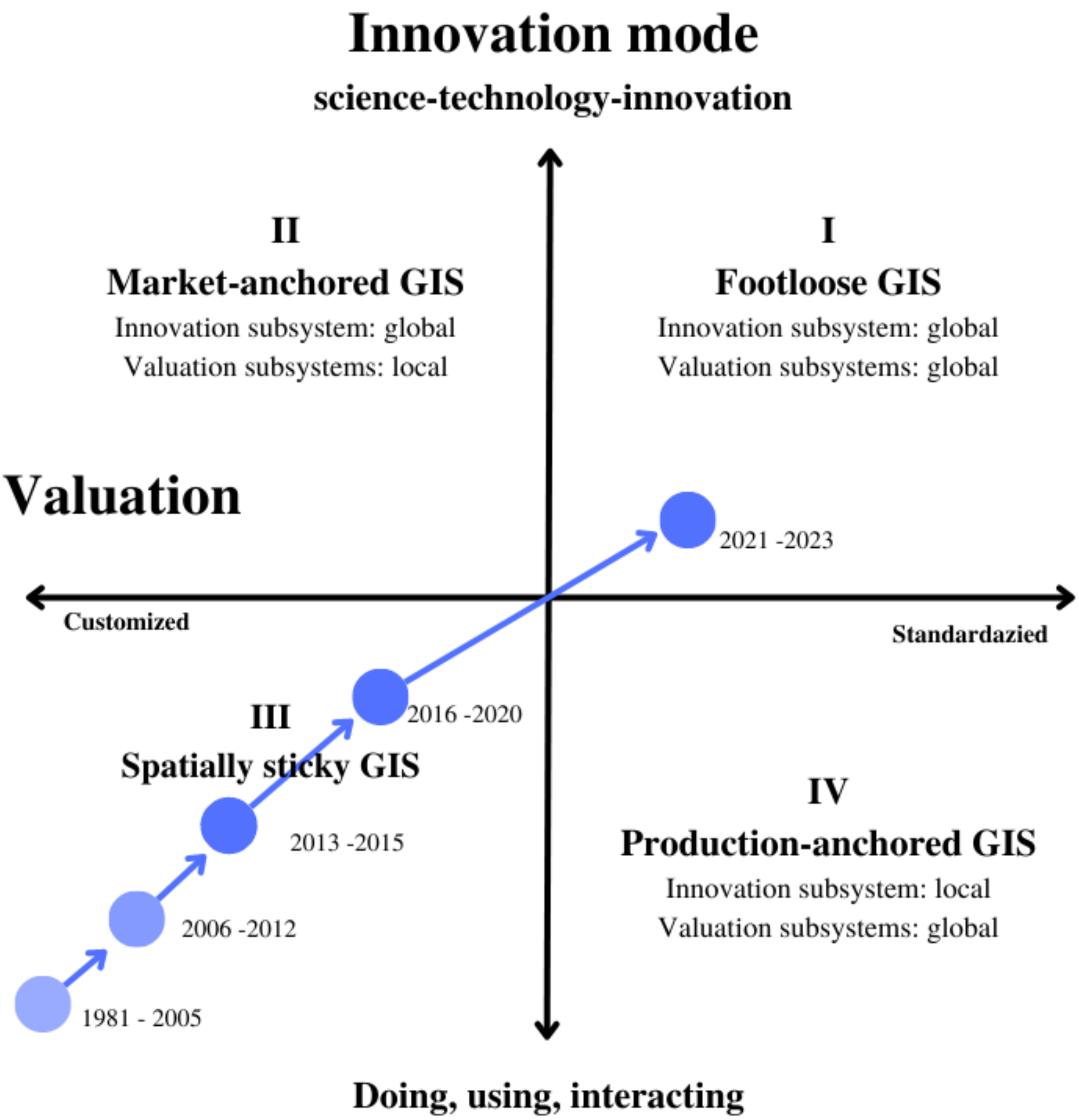


Figure 18, GIS Configurations over time

4.6 Policy recommendations

This section provides a concise summary of the barriers and drivers identified by the interviewees. It is divided according to the four GIS resources, allowing for a systematic examination of each resource to determine what policies per area would enable an advanced maturity of green methanol as a marine fuel.

4.6.1 Financial Investment

Although the commercial adoption of methanol-fueled vessels has been experiencing significant footloose growth, shipowners continue to express deep concerns regarding the availability of an adequate supply of green methanol. Moreover, the maritime industry will face competition from other industries since e-SAF (electrified Synthetic Aviation Fuel) (Ou Lü, 2022), e-diesel, (Gitlin, 2021), and the chemical industry (Dickmann & Dietrich, 2022), will use green methanol as their building block. Highlighting the urgent need for a substantial global increase in production capacity which would enable the fuel to maintain an affordable mass market price as emphasized by GOV, ENG, MFS, RES1, and RES2.

A former member of the trade association expressed that the maritime industry has the potential to magnify the green fuels industry significantly,

> I believe that the maritime sector will play a crucial role in facilitating investments in renewable methanol plants. Once the production for the maritime sector is established, I envision that these plants will explore diversification and consider utilizing their product in the chemical, gasoline, and jet fuel industries. Thereby the alternative fuel sectors will not be competitive but more complementary, emphasizing that the molecule CH3OH serves as the starting point in all cases.

However, before investing in e-methanol plants, another step should be prioritized. As an advisor of the IMO stated,

> If we were to abruptly switch to methanol, ammonia, or any synthetic fuel as an industry tomorrow, it would have devastating effects on greenhouse gas emissions; for green methanol you need green hydrogen, and for green hydrogen you need green electricity, however the current global electricity system is largely dependent on non-renewable sources.

Emphasizing the importance for policymakers to prioritize the establishment of a widespread low-carbon electricity network before the transition to alternative fuels would be truly effective.

Lastly, customers should be incentivized to pay for their pollution, emphasized by GOV, DEC, and MFS. Giving more feasibility for companies to transport their products in a sustainable manner. A member of an NGO explained,

> For approximately 90% of the goods we consume at home, we are not prepared to cover the additional cost for a green supply chain. Emphasizing that if consumers change their demand towards demanding sustainably transported products, the economics of adopting greener fuels would make better sense.

Research by Transport & Environment in 2022 found that sneakers shipped by a container vessel that uses e-methanol from China to Europe would only raise the product price by eight euro cents, highlighting the feasibility of this tactic without levying a heavy financial burden on customers.

4.6.2 Market formation

In the past eight years, regulations surrounding greener shipping have significantly tightened; however, some shipping companies promote that international regulatory bodies should take an even more ambitious stance and strive for the goal of achieving 100% GHG reduction by 2050. A member of the EU parliament commented,

> Achieving zero emissions by 2050 is technically feasible and would avoid escalating costs for future generations. However, the EU is already serving as a frontrunner (70% reduction target by 2050), setting an example for other countries that have not yet made similar commitments. The EU hopes that the IMO will follow suit, but they have been challenging to work with due to its focus on representing industry interests rather than those of member states. This industry-centric approach often hampers the establishment of concrete sustainability agreements.

If the IMO attained higher decarbonization goals, its best option would be to implement a carbon tax system alongside it, as an IMO advisor stated,

> Implementing a carbon tax would be the most straightforward approach bridging the price gap between fossil fuels and green alternatives. It would incentivize investments in technology, optimizing fleet performance, digitalization, and open tons of different possibilities on the fuel side, allowing us as an industry to find the best solution.

While numerous industry experts have expressed their support for more ambitious regulations, it is crucial to emphasize that when new rules are established, it is imperative to consider the interdependencies among all transportation modes. A representative of a company owning a methanol fuelled ship stated,

> Legislation to decarbonize is good as long as it affects everyone who is in the competitive area. Sometimes, we compete with air freight sometimes we compete with land transport and sometimes we only compete with other shipping companies since we are the only ones able to transport certain products across certain routes. Rules should reflect that, so it would not result in an unintended consequence; a shift in demand towards other forms of transportation.

In addition to the decarbonization targets, the production of methanol-fueled vessels could be made less complicated by easing certain stringent safety regulations. A methanol-fueled ship designer stated,

> Handling methanol can pose certain risks in specific situations compared to regular diesel fuel, but it can also be safer in other cases. However, the existing rules do not adequately reflect these distinctions, resulting in additional safety requirements being imposed without fully acknowledging the potential safety advantages of methanol.

4.6.3 Knowledge

Methanol has been used in numerous vessels signifying the viability of using methanol as a marine fuel (Buitendijk, 2020). However, there are still knowledge gaps that can be addressed to enhance the overall sustainability and applicability aspects of methanol as a marine fuel.

A researcher involved in multiple trials with methanol-fueled vessels emphasized to look at a project called the Hymethship (earlier mentioned at p.23). Which could lead to a maritime industry where CO_2 is stored on ships, eventually offloaded at stations on land, synthesized with green hydrogen into green methanol, and again used as a fuel in ships. This concept would radically change the maritime fuel sector; however, as mentioned by the researcher,

> The concept remains futuristic, as more research is required to evaluate the feasibility and safety of storing CO_2 on ships. Additionally, the establishment of numerous land-based CO_2 storage facilities poses another significant challenge. Opening a large area for future research projects.

Moreover, the potential of methanol fuel cells can be more actively explored since these attain higher efficiency results compared to regular combustion methods. A former member of the trade association highlighted the current shortcomings that need to be tackled before these cells can become commercially mature,

> Fuel cells play a vital role in vessels as auxiliary power, marking a significant starting point. Yet, their limited durability and high costs present considerable capital expenditure challenges. Research to enhance these flaws is critical to enhance their viability for vessels.

Furthermore, there is a need for enhanced knowledge sharing among industry professionals on a global scale to fully grasp the benefits associated with the utilization of green methanol in the industry. As emphasized by the former trade association representative,

> With multiple alternative fuels available to decarbonize the maritime sector, each possessing unique characteristics, it becomes crucial to provide a comprehensive overview of the characteristics of these alternatives to potential adopters. Methanol may not excel in every aspect (supply, costs), however, if potential adopters are presented a spider diagram view of every characteristic contrary to other fuels, the clients will truly see that it is the top performer. Nonetheless, effectively communicating this poses a challenge to tackle.

4.6.4 Legitimacy

Over the years, green methanol as a fuel option encountered numerous hurdles hampering its legitimacy, with the largest hurdle being the variety of alternative fuels available, leading shipping companies indecisive as there is no clear sustainable fuel winner.

While hydrogen and electric propulsion emerge as the most viable options at first, being highly efficient fuel choices, the practicality of adopting these alternatives for long-range commercial vessels is impeded by the substantial storage requirements (tanks and batteries) associated with them. This was a consensus among all interviewees. Therefore, fuels with a higher calorific value are needed; as a former member of the trade association explained,

> Waiting until the hydrogen and electricity options are sufficiently developed would not adequately address the pressing environmental concerns at hand. Therefore, shipping companies that do want to decarbonize have to attain fuels with a higher calorific value, and when looking for fuels that are currently attainable and sustainable, methanol, ammonia, LNG, and regular biodiesel emerge as the potential alternatives.

The most straightforward approach to address the legitimacy hurdle would be to advocate for intensified lobbying efforts by the green methanol industry to outcompete other alternative fuels. However, a representative of an NGO explained,

> The future of maritime fuels will require a diverse range of options tailored to specific scenarios. A one-size-fits-all approach is neither realistic nor desirable. Presently, 60 to 70% of globally shipped commodities are fuel-related, which highlights the inefficiency of the current system. It is time to break this inefficiency and instead assess which countries can supply which suitable fuel and make decisions from that perspective.

This would also benefit the adoption rate of methanol. As a researcher involved in maritime methanol trials states: “When being open to all these alternative fuels, and making a choice to adopt/produce one, methanol will most of the times drop out as the winner, thereby eventually taking the largest market share.” Showcasing that the green methanol industry should not promote its fuel as the single alternative fuel winner. Instead, it should spearhead the decarbonization of the shipping sector. Since then, the GIS will create an environment where green methanol, with its merits, garners the market share it rightfully deserves.

5. Discussion

The research conducted provides valuable insights into the dynamic resource maturity and spatial distribution of the green methanol marine fuel GIS. The global scope of the research makes it a pioneering study, as no prior research has examined an innovation on such a wide scale. Moreover, the quantitative and qualitative event history analysis gave a well-rounded dataset to see the flaws of the GIS over time and provide a basis for crucial policy recommendations that should be addressed for the innovation to reach a more mature state. However, it must be emphasized that both the research method employed, and the applicability of the GIS theory have limitations that need to be acknowledged.

5.1 Broad GIS resources

The four GIS resources were initially designed to condense the key functions of the TIS theory into a more manageable framework that could tackle the dynamics of innovation in a global setting (Binz, et al., 2016). However, upon careful reflection of the research, it becomes apparent that the categorization provided by the GIS resources is too general to consistently detect the different maturity phases of the IS across different eras, especially when used for a quantitative analysis. This section shows how the flaws noticed when using the GIS resources could be solved by using the TIS functions from Hekkert et al, (2007) in a next analysis.

Starting with the GIS “Market formation” resource. This resource includes events where entrepreneurs make their first step into a niche market, signifying the start of an IS (Hekkert et al., 2007), but also includes regulatory developments and supportive tax regimes, which are incentives that help an already introduced innovation (Bergek et al., 2008). Showcasing events relating to different maturity phases of the IS. To address this disparity, the TIS theory prescribes two functions; “Entrepreneurial activities”, for activities that happen when an innovation enters a new market segment and “Market formation” which would prescribe the tax and regulatory advancements that protect such a niche market.

The GIS “Knowledge” resource faces a same disparity challenge, entailing both R&D initiatives and knowledge-sharing events. This intertwining creates an intricacy making it difficult to determine whether the circulation of new knowledge to specific subsystems leads to the initiation of R&D projects or if R&D endeavors themselves give rise to subsequent knowledge-sharing events. To present a clearer picture of these feedback loops, it would be beneficial to separate these types of events into two functions. The TIS theory does this by attaining a “Knowledge development” function for R&D projects and a “Knowledge diffusion” function for conferences, workshops, and activities of trade associations.

Lastly, the “Legitimacy” and “Financial investment” resources have exemplified a feedback loop in this research that brought researcher bias. In the case study, the high cost of the fuel hindered the financial investment resource, but also incentivized a lack of interest from relevant stakeholders in the field. There is no clear indication as to which resource such an event would belong to or if it either should be signified to both. Consequently, the researcher makes its assumption where such an event belongs, which cannot be justified (in this research it was signified as negative financial investment events). The TIS framework solves this by proposing the “Guidance of Search” function, a function prescribing the overall general trends in the socio-economic system, including if a technology is generally recognized as affordable or too costly. By including this resource, a true split could be achieved between true “Financial Investment”, statements about the economic viability and other trends of an innovation, and the “Legitimacy” resource that regards positive or negative advocacy of the innovation.

So future research is suggested to incorporate the TIS functions in the global quantitative trend analysis; the research will then probably yield a more accurate numerical picture of the innovation's progression and feedback patterns between the events.

5.2 Limitations of the event history analysis

In this research, an understanding of the GIS development was achieved through a dual data gathering approach, combining a wide-scale event history analysis and interviews. Several flaws were found with the event history analysis, especially when aimed to highlight the effect of specific events, structural couplings among individual players, and examining the specific context in which an innovation is situated, as described to be essential research goals in other IS literature (Heiberg & Truffer, 2022; Binz & Truffer, 2017).

Firstly, the quantitative trend analysis employed in this research failed to accurately reflect the impact of events on the GIS resources. The approach of assigning a score of +1 or -1 to activities, while enhancing replicability and reducing researcher bias, overlooked the significance of certain events or their lack thereof. For example, a highly significant event like the methanol-fueled vessel order by Maersk in 2021 was highlighted in over 50 news articles but received the same score of +1 as a sailing boat that opted for a methanol fuel cell only mentioned in just one article. This limited scoring system fails to capture the relative importance or magnitude of these events. To address this limitation, future research could explore alternative methods to assess the importance of events. One potential approach could involve considering the number of articles that address a specific event/topic, and thereby assign a quantitative value to its importance (such bibliometric analyses are done by other authors as well (Jiang & Liu, 2023; Xie et al., 2021; Castillo-Vergara et al., 2021)). This would provide a more nuanced understanding of the impact of events on the GIS. In this research, this flaw was tackled by using interviews to identify the magnitude of the events.

Secondly, the news articles often provided a brief overview of an event, highlighting the what rather than the why (e.g., an article highlighted a company building an e-methanol plant but skipped the underlying motivations). Therefore, relying solely on a news analysis would not suffice to understand connections and motivations behind events in the industry. This was again solved in this research by interviews, providing valuable information regarding the structural couplings in question.

Furthermore, the integration of a qualitative research method enriches the comprehension of the contextual factors surrounding the GIS. In the empirical case, the initial news article analysis failed to provide a satisfactory explanation for the absence of commercial methanol vessel orders between 2015 and 2020. However, the utilization of interviews with industry experts uncovered a crucial insight: the sharp decline in oil prices from late 2014 played a significant role in this lack of orders. This discovery underscores that solely relying on news articles disregards indispensable contextual information that is vital for grasping the full trajectory of the GIS.

5.2 Limitations of the interviews

The qualitative research has shown its flaws as well. In the early stages, when innovation is still concentrated in specific locations it is relatively easy to identify the key players and their contributions by interviews. However, as the innovation matures and expands across different locations, the abundance of information from multiple actors can become overwhelming, making it more challenging to discern which players remain relevant to interview in the evolving landscape. Consequently, there is a risk of subjective bias, where certain actors are chosen for interviews based on personal judgment rather than their true relevance or impact within the industry. As of this research, most interviewees were chosen with long-lasting careers in the industry, enabling them to highlight events from different maturity phases of the GIS.

5.3 Can the GIS quadrant reflect a complex value chain

Binz and Truffer (2017) raised a critical question if complex value chains that involve inputs from multiple industries can be categorized in the GIS quadrant. The green methanol as a marine fuel GIS exemplifies a value chain built up by several industries. Green methanol is both e-methanol and biomethanol; each produced in very different plants with very differing feedstocks. This product is then incorporated into the maritime value chain, which encompasses various other niche industries such as storage and bunker facilities, ship designers, engine builders, safety rule makers, vessel owners, and others that had to be all individually ready for the adoption of the fuel. Next to that, green methanol is not exclusively produced for the maritime industry but is used as a building block in various other sections. Thereby it can be argued that the shown GIS configuration (Figure 18) is solely an aggregate of all components of separate value chains put together.

Future research could explore analyzing each specific industry involved in a value chain separately and showing which different paths these GIS configurations take. Although such an approach would require additional effort, it could deliver a more comprehensive understanding of the complexities and flaws of certain industries within such a value chain, enabling an enhanced basis for building policy recommendations.

6. Conclusion

This research investigated the drivers and barriers of the green methanol marine fuel GIS. This study pioneered by conducting a truly global-scoped GIS analysis, testing the applicability of the GIS theory to categorize the maturity status of a complex value chain, and explore the potential to leverage this theory to formulate policy recommendations for a more effective diffusion of an innovation. Leading to a report that is both academically and socially relevant, delivering robust insights how the maritime industry can accelerate its decarbonization efforts.

In the research an event history analysis was executed, focusing on the events that played a significant role in shaping or hindering the maturation of the GIS. Through a rigorous news assessment, over 7,000 articles were analyzed, extracting relevant information on industry events, resulting in an extensive and comprehensive database of events. This dataset was further enriched by information from in-depth interviews with ten highly experienced professionals from the green methanol maritime domains.

By integrating both the quantitative and qualitative datasets, the study constructed a robust narrative that delineated five distinct periods, representing pivotal shifts in the maturity of the IS. Notably, green methanol transitioned from being a niche U.S. racing fuel, to a fuel used to comply with sulfur mitigation rules, to a globally recognized marine fuel that enables the decarbonization of the maritime industry, overcoming spatial constraints. However, there are still significant barriers that hinder the widespread integration of green methanol into the industry, showing the necessity of the delineated policy recommendations that bolster the four GIS resources, ultimately fostering the system's maturation.

The analysis identified barriers, including the need to scale up green methanol supply, decarbonize the electricity system for effective e-methanol plants, address the indecisiveness of shipping companies awaiting an alternative fuel winner, and facilitate effective knowledge transfers among industry players. On the other hand, key drivers encompass higher international GHG reduction targets set by the IMO, global recognition of the polluter pays principle, and more R&D efforts towards CO_2 capture on vessels and methanol fuel cells.

While the analysis successfully achieved its objectives, certain flaws were identified in the GIS theory and methodology employed. Specifically, the quantitative GIS analysis fell short in capturing the feedback loops between players and the exact maturity status of the innovation system, suggesting the need for refinement through the integration of functions from the TIS framework. Additionally, relying solely on a news analysis without incorporating interviews proved insufficient in capturing contextual information. However, the interviews also presented challenges, particularly in filtering the most relevant players in highly mature innovation systems due to the abundance of stakeholders. Furthermore, the study suggests that future GIS studies can benefit from deconstructing the value chain of complex innovations, enabling a comprehensive understanding of the various components that influence maturity within the system.

Overall, this report showcases the feasibility of conducting a rigorous global-scale innovation system analysis that delivers policy recommendations with tangible social impact. Demonstrating that the widespread adoption of green methanol has the potential to propel the maritime industry to a net-zero future, revolutionizing the way vessels are powered and safeguarding our planet for generations to come.

7. Appendix

7.1 Interviewees

Function	**Abbreviation**	**Career experience**
EU parliament member	GOV	Member of the EU parliament
NGO associate of a centre that fights for global maritime decarbonization	DEC	Chief technology Officer
Representative of methanol engine building firm	ENG	General manager,
Methanol fuelled ship designer	DES	Owner
Representative of a waste to methanol plant	WTM	Manager business development
Researcher involved in methanol fuelled vessel trials	RES1	Senior researcher
Researcher involved in drivers and barriers of methanol as a marine fuel study	RES2	Junior researcher,
Former representative of the methanol trade association	TAS	Overall expert, now consultant
Advisor of the IMO and maritime decarbonizing consultant	ADV	Head of green transitions
Representative of a company owning a methanol fuelled ship	MFS	Head of sustainability

Table 6, Specifications of the interviewees

7.2 Interview Scheme

Topic	Key points
Background information	o Actors' expertise o Size of institution o Background of institution in other industries o Date of entering (e-)methanol industry o Reason(s) for entering the industry o Reason for inciting or contributing to the event o Comprehensive description of the event o Effects of the event
Points that may be discussed regarding the knowledge resource (if applicable)	o Did the event influence R&D expertise o Did the event influence workshops and conferences o Did the event influence knowledge networks o Did the event influence the development process of the product
Points that may be discussed regarding the Niche markets resource (if applicable)	o Did the event influence niche markets investments o Did the event influence tax regimes o Did the event influence specific regulations o Did the event influence subsidies
Points that may be discussed regarding the Financial Investment resource (if applicable)	o Did the event influence mobilization of financial capital o Did the event influence sufficiency of financial resources o Did the event influence sufficiency of resources for key actors
Points that may be discussed regarding the Legitimacy resource (if applicable)	o Did the event influence interest groups o Did the event influence lobbying activities o Did the event influence institutional entrepreneurship
Additional drivers and barriers for successful diffusion of the innovation	o Benefits or issues with other actors in the industry in general o Context difficulties with other actors o Unexpected mechanisms or barriers
Concluding remarks	o Outlook on e-methanol as a marine fuel o What the interviewee would like to see changed in the industry or policy

Table 7, interview script based on Binz et al., 2016

7.3 ECA Zones

Figure 19, ECA Zones (THOR Marine Trading, 2023)

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