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Sectoral and technological systems of environmental innovation: the case of marine scrubber systems

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ABSTRACT: The maturing literature on innovation has recognized the processes of sectoral and technological systems of innovation as helpful frameworks to analyze environmental innovation – a field whose importance continues to grow amidst contemporary regulatory pressures, for example, on maritime industry and shipping. This paper intertwines these key innovation concepts and applies them to classify and systematize an environmental product innovation: marine scrubber systems. The paper also addresses the linkage between innovation policy and environmental regulation and presents an overall framework to visualize and systematize conceptual connections between sectoral and technological systems of innovation to further develop and manage these complex systems of environmental innovation inducement. The paper applies technological and legal materials depicting the context of maritime scrubber systems as technological responses to more rigid environmental regulation by addressing their implications for market potential and change. The results underline the importance of environmental regulations as the driver of the development of technological innovation systems centered on environmental innovation.

KEYWORDS: Environmental innovation; marine scrubber system; maritime industry; sectoral system of innovation; technological system of innovation

1 INTRODUCTION

Environmental innovation – defined as "innovations that consist of new or modified processes, practices, systems and products, which benefit the environment and so contribute to environmental sustainability" (Oltra and Saint Jean, 2009: p.567) – are often considered as a response to regulatory pressure induced by policy measures. However, recent studies have suggested that environmental innovation are also engendered by the technological regime of sectors and market demand (Oltra and Saint Jean, 2009). Still, the majority of the literature on environmental innovation from an innovation systems perspective has generally focused on the inducement impact of regulations and other policy measures (Beerepoot and Beerepoot, 2007; Rogge and Hoffmann, 2010) rather than on actual innovation processes (Oltra and Saint Jean, 2009; Galliano and Nadel, 2015). Therefore, much in line with Köhler et al. (2013), this paper adopts an integrated approach for analyzing responses to environmental/innovation policies by addressing how the combination of two (closely related) innovation systems approaches – sectoral systems of innovation (SSIs) and technological systems of innovation (TSIs) (Carlsson and Stankiewicz, 1991; Malerba, 2002) – can contribute to the analysis of environmental innovation. However, this approach goes beyond the traditional focus on policy measures and innovation inducement by incorporating other technological and demand factors affecting sectoral innovation processes and the adoption of new technologies.

Marine scrubber systems (MSSs) are utilized here as an example of how to apply the SSI and TSI frameworks for analyzing environmental innovation. MSSs, cleaning units fitted into exhaust pipes of ships to reduce emissions, are thus a fitting example of environmental innovation (or eco-innovation), in that they match perfectly with the above given definition of environmental (product) innovation (Oltra and Saint Jean, 2009; Makkonen and Repka, 2016). Their production includes, as will be shown in this paper, the interplay between sectoral conditions, markets, and policies grounding their use as an applicable empirical study subject. Their development and current demand can be traced back to the efforts of the maritime sector to comply with recent environmental regulations introducing more stringent emission limits for shipping set in motion by the International Maritime Organization (IMO) to protect human health and the environment in endangered geographical settings.

As stated by Neely (2005), the overreliance on a single concept or framework can impede the empirical and theoretical validity of scientific research, thus creating a need for integrating different approaches. This paper follows that guideline and presents the following goals for itself: 1) bring the TSI and SSI frameworks conceptually closer together to form an overarching heuristic to facilitate the investigation of innovation dynamics in emerging industries that are not well captured with conventional TSI or SSI approaches, and 2) to give an empirical example of how the developed integrated framework can be utilized by mapping the SSI of the maritime industry and particularly the TSI of MSSs; identifying the factors that have led to the development of MSSs; and pinpointing the key processes in the formation of MSS technology. In doing so the paper is answering the call voiced by Oltra and Saint Jean (2009) to investigate environmental innovation more thoroughly and more formally through the coevolution of the building blocks that constitute sectors, and through the evolution of the boundaries between these sectors. This aspiration is in line with various recent innovation system studies (e.g. Coenen and Díaz López, 2010, Coenen et al., 2012; Quitzow, 2015; Stephan et al., 2017), which have argued that, especially in the realm of environmental innovation, such integrated approaches are urgently needed.

The paper proceeds as follows. First, a brief overview and a synthesis of the conceptual backgrounds of SSIs and TSIs are given to justify the need for integrated approaches, followed by the description of the employed framework that bridges SSI and TSI perspectives together. Second, the employed empirical approach is outlined and its limitations discussed. Third, the results showing how the TSI of MSSs, induced by regulatory pressures, has evolved through interlinked environmental and innovation policies, technology conditions and market demand to a solution that now offers a viable method for shipping emission abatement are presented. Finally, the paper concludes with a discussion of its most pertinent implications by summing up its empirical, theoretical, and policy relevance.

2 CONCEPTUAL BACKGROUNDS

2.1 Sectoral systems of innovation

Observations of the major differences between the patterns of innovative activities in distinct sectors and their similarity across different countries has led to the coining of the concept of SSI. The concept was thoroughly introduced into the literature by Malerba (2002, 2004). In contrast to its closely related geographically delineated counterparts, that is, national systems of innovation (NSIs) and regional systems of innovation (RSIs) (Lundvall, 1992; Cooke, 1992), in this approach sectors are utilized as units of analysis. SSIs have been defined as “a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products” (Malerba, 2002: p.250). Here, following Oltra and Saint Jean (2009) and Faber and Hoppe (2013), SSIs are discussed through the following interlinked themes: agents, interactions, and networks; technological regimes; market demand; and policy conditions.

Agents, interactions, and networks: As stated by Faber and Hoppe (2013: p.631), "any sectoral system analysis involves an overview of the main agents in the sector, including their interactions and formal as well as informal networks." The basic characteristics of an SSI can thus be described through the agents (firms, universities, financial institutions, government, local authorities, individuals, etc.) involved, their interactions, and the networks that have been formed due to these interactions (Malerba, 2002). The agents can be further divided into primary and secondary agents. Primary agents are the key players of innovation within the sector, that is, (commonly) innovative firms. Secondary agents are supporting organizations such as the government, banks, research institutes, consultancies, and intermediaries (Faber and Hoppe, 2013).

Technological regimes: Firms operate within sectors characterized by distinct technological environments, that is, technological regimes, which play a key role in determining their patterns of innovative activities. There are two types of technological regimes: 1) an entrepreneurial regime (characterized by a continuous enlargement of the innovation base through the entry of new innovators) and 2) a routinized regime (characterized by the dominance of a few established continuously innovating firms) (Malerba and Orsenigo, 1997; Oltra and Saint Jean, 2009). Since new technologies can open up opportunities for firms to take advantage of, the discussion related to the role of technological barriers to entry has led Marsili (2002) to the argument that the complexity of the technology (the knowledge base upon which it is based) involved within a sector determines to a large extent the likelihood of the emergence of new actors entering into the sector (the higher the complexity, the higher the entry barriers). The transportation sector, also discussed in this paper, is characterized by high complexity, which thus sets entry-barriers for new firm (centered on eco-innovation) formation.

Market demand: Traditionally, innovation studies have concentrated on supply side dynamics, whereas the demand side of innovation attracted little scholarly attention (Oltra and Saint Jean, 2009). Two notions challenged this passive voice given to market demand: 1) the notion of the emergence of dominant design (Abernathy and Utterback, 1978) and 2) the notion of increasing returns on innovation adoption related to, for example, scale economies in production and technological interrelatedness (Arthur, 1988). It was realized that market demand conditions can potentially lead to a technological monopoly and an era of incremental improvements (Oltra and Saint Jean, 2009). However, new disruptive innovation can displace a dominant technology if there is a willing group of niche consumers adopting and experimenting with new technologies (Malerba et al., 2007). The incentive for firms to develop environmental innovation can thus come from the market through the non-regulatory pressure of "green consumers" (Foster and Green, 2002; Oltra and Saint Jean, 2009). Firms should also consider the market as a potential cooperation partner by integrating users into the development processes of environmental innovation (Wagner, 2009; Carrillo-Hermosilla et al., 2010).

Policy conditions: Since technology-push within a sector and market-pull alone do not seem to be strong enough incentives for environmental innovation, public policies aimed at facilitating sustainability (regulatory push/pull effects) are commonly needed (Rennings, 2000). Policies can be aimed at facilitating demand-pull or technology-push conditions of environmental innovation depending on how they are designed (Oltra and Saint Jean, 2009). Demand-pull policy instruments are measures aimed at raising the payoff of successful innovations through activities such as environmental regulations, standards, and taxes on competing technologies. Technology-push policy instruments are measures targeted at incentivizing innovative activities by reducing the costs of developing environmentally friendly products, services, and processes through, for example, tax credits and direct funding for research and development (R&D) (Nemet, 2009; Makkonen and Repka, 2016). The combinations of these policy instruments define the environmental innovation policy mix that is utilized for promoting sustainable sectoral systems of production and consumption (Oltra and Saint Jean, 2009). This policy mix is influenced by varying geographical scales, since the policies can be designed at local, national, or international levels. It is rather unsurprising that the exact policy mix or individual measures that would be the most effective at producing the best results remain elusive (Costantini et al., 2017). Despite this uncertainty, it is commonly agreed that regulations (and other policy instruments) play an important role in shaping the functioning of SSIs in connection to environmental innovation (Oltra and Saint Jean, 2009; Faber and Hoppe, 2013).

2.2 Technological systems of innovation

Distinct from its geographical (RSIs and NSIs) and sectoral (SSIs) counterparts, in TSIs the unit of analysis is a specific technology or product. The concept was coined by Carlsson and Stankiewicz (1991: p.111) and was defined as “a network 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.” A TSI does not necessarily exist in every arbitrarily chosen field, rather a TSI needs to meet a certain set of conditions. There should be 1) a variety of different actors pursuing different innovation strategies, 2) a certain division of labor between these actors, 3) a variety of (lobbying and classification) institutions, and 4) at least some market transactions (Markard and Truffer, 2008).

Hekkert et al. (2007) and Bergek et al. (2008) have introduced practical schemes for evaluating the overall functioning of a TSI, which is impacted by key processes (termed functions) that can be potentially influenced by policy-makers. This “functions approach” has been extensively applied in a wide range of studies of environmental innovation, sustainability, and technological change (e.g. Negro et al., 2008; Suurs and Hekkert, 2009; Foxon et al., 2010; Suurs et al., 2010; Tigabu et al., 2015; Reichardt et al., 2016). The functions approach is employed here as an analytical framework for describing the TSI of MSSs by tracing the following steps: structural components; functional patterns; and policy issues.

Structural components: The focus of research on TSIs can be placed on a distinct knowledge field or product (here the emphasis is placed on a product, namely MSSs). Thus, the analysis starts with identifying the actors involved as well as the networks that exist between them. The actors commonly include firms, universities, research institutes, public bodies, etc. Moreover, institutions (through laws and regulations) influence the TSI in question (Jacobsson and Bergek, 2004; Bergek et al., 2008).

Functional patterns: For any analysis to go beyond the mere description of the structure of a TSI it is necessary to move on to analyzing its functions (or key processes). These functions include the following (Hekkert et al., 2007; Bergek et al., 2008): 1) knowledge development and diffusion, 2) influence on the direction of search, 3) entrepreneurial activities/experimentation, 4) market formation, 5) legitimation, 6) resource mobilization, and 7) development of positive externalities.

The first function naturally refers to the knowledge base of the TSI (types and sources of knowledge). The second refers to incentives to enter into the sector and the selection between various technological options including beliefs in future growth potential due to regulatory pressures and/or articulation of interest by customers. This function can be fulfilled by a variety of agents such as the government and/or the market. The third function is about probing into the new technology and applications through experimentation, potentially turning new knowledge into concrete actions. The fourth function concerns the evolution of markets and demand for a specific product or technology through three (potential) phases: from an early nursing market for contemporary niche products, through a more voluminous bridging market, and eventually into a dominant mature (or mass) market. The fifth function is a matter of acceptance of the new technology by relevant institutions. The sixth function is related to partnerships and the human and financial capital that the TSI can mobilize. Finally, the development of positive externalities from new firms entering the TSI concerns the emergence of pooled labor markets, emergence of specialized goods and service providers as well as knowledge spillovers. Some authors (e.g. Andreasen and Sovacool, 2015) include benefits that occur for the society as a whole, such as reduced emissions, to this list. These functions are not completely independent from each other, rather they form a sequence of processes where the individual functions coevolve (Hekkert et al., 2007; Bergek et al., 2008).

Policy issues: The internal dynamics of a TSI alone are only a partial explanation of its success: inducement and blocking mechanisms influence the functioning of a TSI. For example, a strong belief in the growth potential of a specific technology or a new government policy (such as tax credits or cheap loans) on conducting R&D can act as an incentive that promotes the development of a TSI. In contrast, blocking mechanisms, such as a poorly developed market for a product, can have strong negative impacts (Jacobsson and Bergek, 2004; Negro et al., 2012). Policies should target TSIs by measures that strengthen inducement mechanisms and remove blocking mechanisms (Bergek et al., 2008).

2.3 Conceptual framework: Boundaries of sectoral and technological systems of innovation

As discussed by Malerba (2002) and Oltra and Saint Jean (2009) the literature on SSIs should pay close attention to the evolution or transformation of boundaries between sectors. This is particularly relevant for environmental innovation, which can often be a product of combining different technologies present in various distinct sectors (Cooke, 2008). Therefore, when discussing environmental innovation, one commonly studies a field that has combined existing technology from various sectors in an integrative manner. Similarly, TSIs commonly cross sectoral and geographic boundaries (Figure 1) (Markard and Truffer, 2008; Stephan et al., 2017). Therefore, caution is required when setting (definite) sectoral and/or territorial boundaries for TSIs (Bergek et al., 2015).

A TSI can be a subsystem of a SSI (a knowledge base which is exclusive to an individual sector) or an amalgamation of several related sectors (a more generic knowledge field involving many sectors) (Bergek et al., 2008; Markard and Truffer, 2008). TSIs can be geographically bounded in a region (RSI) or a nation (NSI) but are more commonly international, or even global, in nature (Binz et al., 2014; Binz and Tuffer, 2017). In fact, Bergek et al. (2015) have noted that definite delineations of TSIs according to, for example, the borders of countries do not follow the actual definition of the concept.

<Figure_1>

The different innovation system approaches are, thus, closely intertwined. Therefore, also the two approaches discussed here inevitably overlap. This is evident, for example, when considering the actors and interactions necessary for both SSI and TSI emergence: “agents, interactions and networks” of the SSI approach are conceptually (relatively) similar to “structural components” (i.e. a network of agents) identified in TSI. Moreover, the functional patterns of the TSI approach can be shown to relate to one or more of the three building blocks constituting SSIs, or vice versa (Figure 2). Still, in the literature on environmental innovation it has been quite common to conceptually delineate a theoretical approach that “fits best” to the interest/purposes of the study (Hekkert and Negro, 2009). Here, however, neither the SSI nor the TSI approach is presented as the only suitable tool for analyzing environmental innovation. Contrarily, they are discussed side-by-side in the results section (Section 4) to showcase how these two approaches, rather than being exclusive, can analytically complement each other (dos Santos Silvestre and Dalcol, 2009).

<Figure_2>

Figure 2 indicates the main connections between the SSI and TSI approaches. Clear cut distinctions are naturally hard to make. For example, public policy could be linked to the other functions of TIS not highlighted in the figure: market formation e.g. by imposing higher taxes for competing technologies, knowledge diffusion e.g. by supporting the implementation of the technology, entrepreneurial activity/experimentation e.g. by supporting start-ups and pilot projects, and development of positive externalities e.g. via educational and training programs. However, for the sake of clarity, here only the most “obvious” connections identified in our empirical case (Section 4) were signaled out and, for example, the role of public policy is largely discussed through its influence on the direction of search (regulatory pressures), legitimation (the acceptance of MSS as an abatement method by relevant institutions) and resource mobilization (the success of the TSI in receiving financial support via public policies). These presented interdependencies between the two approaches function here as an amalgamated framework guiding the analysis of the formation of the TSI of MSSs.

3 SCHEME OF ANALYSIS

After scrutinizing alternatives, we decided that the most viable approach, in line with Laaksonen and Mäkinen (2013), for the purposes of this paper (to analyze the interplay between MSS technologies, environmental regulations, technologies, and market demand) was a desk study. The approach combines and applies existing academic literature, documents and data on TSI and SSI concepts together with empirical examples of MSSs (supplemented here with interviews with industry experts). This was accomplished by reviewing documents and existing studies of legislation requirements, MSS properties, and their implications for innovation. Specifically, we gathered and interpreted the relevant material via accessing:

1) The academic literature (search procedures in Scopus and Google Scholar by employing keywords such as “scrubber”, “emission control”, “emission reduction”, “emission regulation”, and “exhaust gas cleaning”)

2) Web pages and associated documents of relevant industry and classification associations/societies including DNV LG (www.dnvgl.com) and Exhaust Gas Cleaning Systems Association (EGCSA) (www.egcsa.com)
3) Relevant policy documentation by IMO and the European Union (EU)
4) Web pages, annual reports, press releases and associated news of MSS manufacturers (member of EGCSA)
5) Leading industry experts in the field based on interviews and e-mail correspondence with representatives of Finnish MSS manufacturers: Langh Tech (Product Manager, 17.11.2017), Valmet (Senior Manager, 13.12.2017), and Wärtsilä (Senior Advisor, 7.11.2017)

These documents and insights give us a coherent picture of the history, milestones, and interplay between the policy conditions, technology, and market demand that has led to the development of the TSI of MSSs.

It has to be noted that the commonly identified caveats of case studies apply also here. For instance, it is often stated that case study results are hard to generalize beyond the case addressed and that their objectivity is questionable (Hodkinson and Hodkinson, 2001). However, these “traditional” views have been refuted by scholars, who value the role of case studies as an educational tool for knowledge creation. For example, Flyvbjerg (2006) regards the above-mentioned caveats more as “misunderstandings” and therefore has corrected them by stating that one can often generalize on the basis of a single case and that case study research contains no greater bias towards subjectivity than any other method of scientific inquiry.

4 THE CASE OF MARINE SCRUBBER SYSTEMS

4.1 Backgrounds and feasibility

The rationale for combining the domain of legislation into discussion of environmental innovation comes forth from the understanding of public governing organs (national and international) as actors that can, on the one hand, support green technologies and, on the other hand, direct the development of SSIs and TSIs into a more sustainable direction. This very much applies in the case of MSSs, since their “origin” can be traced back to international policy measures. IMO is a specific United Nations organ that regulates global maritime issues and shipping.

The agenda of the International Convention for the Prevention of Pollution from Ships (MARPOL) has produced a number of annexes stating guiding regulations on shipping. Air pollution is covered in Annex VI (providing guidelines for the current regulations and the continuous decrease of sulfur content in marine fuels and emissions), which was adopted by IMO in 1997 (marking the start of the discussions on how to meet the restrictions), ratified in 2004 and came into force in 2005. A revised version of Annex VI (permitting MSSs as an abatement method) was adopted in 2008. EU obligated it member states to follow it, either via fuel-based or technology-based compliance, through Directive 2012/33/EU. Since January 1, 2015, ships operating in the four designated Sulphur Emission Control Areas (SECAs) – North American (coasts of Canada and USA), US Caribbean Sea (Puerto Rico and US Virgin Islands), Baltic Sea and North Sea – are expected to reduce their emissions to a limit equivalent to having no more than 0.1% sulfur content in their marine fuel (Figure 3). Globally, the limit will be lowered to 0.5% in 2020. A more stringent 0.1% limit (set in Directive 2016/802/EU) will be implemented in EU-ports. Moreover, since 2016 China has started to designate “local” SECAs (key ports in Yangtze and Pearl River Deltas and Bohai Sea) that have already implemented the 0.5% limit. These key dates also largely determine the dynamics of the technological regime and market demand for MSSs development, divided into distinct time phrases: I) early development phase from 1997 to 2007, II) moderate growth phase from 2008 to 2013 and III) high growth phase since 2014 (see also Figure 6).

<Figure_3>

In practice, IMO regulation requires either the use of fuels with lower sulfur content than heavy fuel oil (HFO) – such as liquefied natural gas (LNG) or light fuel oil (LFO) – or the incorporation of exhaust cleaning MSSs on new builds or retrofitting them onto existing vessels. The latter option would enable the ships to operate with cheap HFO (Lähteenmäki-Uutela et al., 2017). There are two main categories of MSS: wet scrubbers (open, closed, and hybrid systems) and dry scrubbers (Figure 4).

<Figure_4>

The main “axes” on which MSS technologies balance are their cleaning efficiency, size, and cost (whether they are a technologically and economically feasible option for shipping companies). The technological feasibility of MSSs to reduce sulfur oxides (SO_X) emissions under the corresponding IMO limit of 0.1% sulfur content in the fuel has been proven in a range of recent studies (e.g. Seddiek and Elgohary, 2014; Fridell and Salo, 2016). Studies have reported that the more stringent environmental regulations have led to a reduction (from 50% up to 85%) of SO_x emissions in the SECA regions (den Boer et al., 2016; Zetterdahl et al., 2016). Naturally, it is impossible to give an exact figure of the share of MSSs in this reduction, but for example Seddiek and Elgohary (2014) have shown that between the different abatement methods, using MSSs is among the ones with the highest potential for reducing shipping emissions. Indeed, tests have shown very high SO_x removal efficiencies (up to 93–98%) for MSSs (Hansen, 2012; Caiazzo et al., 2013; Tran, 2017).

However, the economic feasibility of MSSs has still been under considerable debate (Makkonen and Repka, 2016). At the moment, for ships operating both in- and outside of SECAs, dual fuel machinery allowing the ships to use fuels with different sulfur contents (HFO and LFO) seems to be the optimal solution in economic terms (Yang et al., 2012; Patricksson and Erikstad, 2017), whereas LNG appears the optimum proposed solution when both the environmental and the economic points of view are considered (Ammar and Seddiek, 2017). However, MSSs seem to be cost-effective for vessels operating mainly or entirely within SECAs (Ciatteo et al., 2014; Carr and Corbett, 2015): it has been estimated that for Finnish shipping companies alone, fitting MSSs into ships would bring cost savings around 62-85 million Euros a year compared to switching to more expensive fuel types with lower sulfur content (Kalli, 2012).

For an individual ship, the payback time of installing MSS has been estimated, dependent on contemporary fuel prices, to be around two years: it makes more sense to install an MSS on new ships than to retrofit them onto old ones (Bergqvist et al., 2015). If an old ship has a limited remaining life-span, retrofitting an MSS is not an economically viable option (Jiang et al., 2014). Thus, the decisions need to be taken on a ship-to-ship basis, based on the ship itself (age and type: the price range of MSS can vary between one and six million Euros depending on its type and the type of the ship), fuel prices, and the proportion of operations inside SECAs (Makkonen and Repka, 2016).

4.2 Sectoral and technological systems of innovation and marine scrubber systems

4.2.1 Agents, interactions and networks

MSSs are considered here as a TSI that combines knowledge from various sectors but is “situated” mainly within the SSI of maritime industry. A recent study by Karvonen et al. (2016) has mapped the SSIs of the maritime industry, including the central agents and the networks and interactions involved in the development of new products and services. Since, the agents and interactions of the SSI approach are conceptually (relatively) similar to “structural components” (i.e. a network of agents) identified in TSIs, after minor modifications, the depiction provided by Karvonen et al. (2016) is relevant also here (in the case of the TSI of MSSs) as illustrated in the Figure 5.

<Figure_5>

The structural components (or agents, interactions and networks) involved with MSSs can be considered a TSI, since it includes a variety of different actors pursuing different innovation strategies, a certain division of labor between them, market transactions (as evidenced by MSS installations and orders) and classification and lobbying institutions. Moreover, as will be shown below the TSI of MSSs includes knowledge and actors from more than one SSI and these actors are active in many different NSIs (including e.g. Finland, Denmark, and China). Therefore, the TSI of MSSs can be considered as a TSI_3 -type of TSIs presented in Figure 1. The initial “call” for MSSs came from IMO through the regulations on limiting SO_X emissions for ships operating in SECAs. This led the primary agents of the system, that is, MSS manufacturers in association with subcontractors and consultancies/planning companies adapt already existing technologies (mainly from the electric power, clean tech, and manufacturing industries) to meet the needs of shipping operators (Makkonen and Repka, 2016). The different MSS manufacturers have often concentrated on different types of MSS technology (open, closed and hybrid systems) and different market segments (container ships, cruiser ferries, etc.), while various subcontractors produce different parts and equipment needed for MSSs.

The development work was facilitated by collaboration with secondary agents such as universities and public research institutes and support from governmental funding agencies. International classification societies (such as DNV GL) issue certification for MSSs and “monitor”, together with flag-state administration, their compliance with emission limits (Martinvuo-Helo, 2011; Seddiek and Elgohary, 2014). In terms of lobbying institutions, initially IMO regulations were met with heavy resistance from shipping operators and much of the lobbying was directed against implementing the sulfur limits (Gritsenko and Yliskylä-Peuralahti, 2013; Bloor et al., 2014). However, there were also “green” lobbying groups in favor of IMO regulations (Sys et al., 2016), whereas EGCSA has been successful in promoting the MSS technology as an abatement method (Hermann, 2017). This description of the TSI of MSSs functions here as the backdrop for evaluating the factors that have led to the development of the system.

4.2.2 Technological regimes

Early development phase – Different types of scrubber systems have been in wide use, for example in power plants. This technology has, however, only recently been applied in shipping (Bergqvist et al., 2015). It was the interplay between actors involved in multiple sectors (shipbuilding, shipping, manufacturing, electric power, and clean tech) that finally produced MSSs as an innovative means to tackle environmental issues in shipping. Many of the contemporary MSS manufacturers also operate outside the maritime industry and have extensive experience and capabilities of manufacturing scrubber systems for other purposes. Therefore, in the case of the TSI of MSSs the first function (*knowledge development and diffusion*) refers to the existing knowledge that many of the MSS manufacturers had acquired previously with similar systems implemented in, for example, the electric power and manufacturing industries.

The existing technologies, thus, guided the second function (*influence on the direction of search*) of the TSI of MSS. This knowledge combined with expertise on specific shipping requirements that existed in the maritime sector, corresponding to the sixth function of the TSI of MSS (*resource, particularly human capital, mobilization*), contributed to the development of know-how within the TSI and ultimately led to the first MSS fitted to vessels in line with the third function (*entrepreneurial activities/experimentation*) of the TSI of MSS. Still, extensive R&D was needed for MSS manufacturers to modify existing scrubber techniques to fit the shipping industry to fit this knowledge into the shipping context (Makkonen and Repka, 2016). This work has been supported by the EU and, for example, in Denmark and Finland by the government.

Moderate growth phase – The knowledge required for developing MSSs has thus existed for a long time. However, until very recently there seemed to be no actors willing to take advantage of this technology. In fact, there are still only a limited number of MSS manufacturers (e.g. EGCSA has 22 full members). This underlines the routinized nature of the technological regime involved in the creation of MSSs, arguably due to the high complexity of MSS technology and the lack of demand prior to the announcement that IMO regulations were to be enforced on shipping. The development work towards MSSs was first initiated in firms situated in countries heavily affected by SECAs: for example, Wärtsilä (a Finnish MSS manufacturer), became the first company in the world to receive a certification to its scrubber in 2009 (Figure 6).

High growth phase – The implementation of SECAs in 2015 attracted more manufacturers into the field, a process that has intensified due to the closing in of the global sulfur limit and the designation of local SECAs in China. For example, in 2017 Bluesoul became the first Chinese MSS manufacturer to be awarded an Approval in Principle (AiP) in recognition of the technical feasibility of their scrubber (Figure 6). The TSI of MSSs has therefore been able to extend its socio-economic impact mainly through growth of the established actors but also to some extent through new firms that have entered the TSI either as MSS manufacturers or as subcontractors. For example, in Finland, this has led to positive gains in terms of knowledge spillovers, the labor market and the Finnish economy. This development corresponds with the seventh function (*development of positive externalities*) of the TSI of MSS.

4.2.3 Market demand

Early development phase – By the time that IMO regulations were first formulated in 1997, the question of how to meet these demands was an open one – MSSs were created as an option for abatement. At first their cleaning efficiency and their actual costs remained elusive (Reynolds, 2011). Moreover, MSSs demand space within the ship, which proved to be problematic in some cases. It was economically risky for the early movers to test the technology, resulting in a low non-regulatory pressure from “green consumers” (Bloor et al., 2014) – for example, as late as early 2013 there was still only one MSS installed (Containerships VII) within the entire Finnish commercial fleet (except for pilot projects) (Figure 6). Initially, the interest from shipping companies towards installing MSSs was highest for companies whose ships were operating mainly within SECAs.

Moderate growth phase – The designation of SECAs and the anticipated stricter limits on ships’ SO_X emissions globally gave the MSS manufacturers a sufficiently strong belief in the future growth potential of the field heightened by the rise in the articulation of interest by the customers. This corresponds to the second function (*influence on the direction of search*) of the TSI of MSS. In the early phases of MSS technology, shipping companies reported technical difficulties relating to the wastewater generated. MSS manufacturers were trying to resolve these problems in close collaboration with the shipping operators. The few shipping companies experimenting on the technology and testing the equipment onboard (e.g. the Danish DFDS and Finnish Langh Ship) in partnership with the MSS manufacturers were thus integrated into the development processes of MSSs as test beds – in line with the third (*entrepreneurial activities/experimentation*) and sixth (*resource mobilization*) function of the of the TSI of MSS – for the emerging environmental innovation.

High growth phase – Although MSSs have been applied on an experimental scale before (Ren and Lützen, 2015), the high price and early technical difficulties of MSSs remained an issue for shipping companies (Reynolds, 2011; Bloor et al., 2014) until just before 2015 when the sulfur limits took effect in SECAs (national agencies, such as the Finnish Transport Safety Agency and the US Environment Protection Agency, do random inspections on vessels operating in their territorial waters), which led to a significant boost in MSS installations (Figure 6). The demand for MSSs, thus, started to grow only when the implementation date of the policy measures from IMO was closing in. Since then, technical difficulties have become rare(r) and the demand for MSSs has grown gradually.

MSSs have been estimated to become more popular internationally in the future due to the globally imposed sulfur limit of 0.5% to be realized in 2020 (Bergqvist et al., 2015; Makkonen and Repka, 2016). According to industry experts, this already shows in the most recent figures on MSS tenders and orders. Therefore, the fifth function (*legitimation*) in the case of MSSs is related to the acceptance of the new technology by the shipping operators, which have by now indeed adapted MSSs as one option for SO_X emission reduction. The fourth function (*market formation*) of the TSI of MSS has, thus, followed the evolution of markets and demand for a specific product or technology through the phases identified in Section 2.2. Firstly, an early nursing market – i.e. the shipping operators that were willing to test the product as a future means of achieving the SO_X emissions targets – for MSSs as a niche product was formed prior to the date of implementation of IMO regulations. At first the demand for MSSs remained sluggish, but when the actual date for IMO regulations to come into force neared, the demand for MSSs started to rise (a bridge market). As there are alternative abatement methods that shipping companies can utilize, MSSs have not, however, reached the stage of having a dominant mature market. For example, the International Energy Agency has estimated that only 2.2% of the global fleet will have MSSs installed by 2020. Therefore, the underdeveloped market demand remains a major blocking mechanism for the TSI of MSSs.

4.2.4 Public policy

Overall, a recent analysis has suggested that the contemporary growth in emissions-related patents within the maritime industry and IMO documents imposing more stringent emission limits are correlated (Corbett et al., 2016), lending support to the usefulness of environmental regulations to induce eco-innovation. As stated in a recent review on environmental innovation and innovation policies (Bergek and Berggren, 2014): general regulatory instruments enforce improvements based on application of better solutions that meet new requirements. The contemporary debate on innovation policies stresses that both innovation support and environmental regulations are needed for sustainable transitions toward more environmentally friendly solutions: innovation policy (support for R&D, pilot projects, etc.) is the key for cutting costs of environmental innovation in the invention and market introduction phases, but without punishing, destabilizing, or internalizing external costs to the existing non-ecological products, processes, or services competition will be distorted in favor of the cheaper but environmentally harmful solutions (e.g. Rennings, 2000; Alkemade et al., 2011; Kivimaa and Virkamäki, 2014; Kivimaa and Kern, 2016; Uyarra et al., 2016).

Early development and moderate growth phases – The above notions apply also in the case of the TSI of MSSs: the combination of IMO regulations and supportive national and EU innovation policies made MSSs a feasible technology for emission abatement. Innovation policies facilitated MSS manufacturers to develop and produce MSSs and the shipping operators to install them onto their vessels, but they would not have been developed without the more stringent emission limits. Moreover, the demand for MSSs remained sluggish prior to the enforcement of IMO regulations (Figure 6).

As such, IMO regulations were the main catalyst for the development of MSSs. In addition to being mainly an environmental policy aimed at decreasing the detrimental impacts that shipping can have on human health and the environment, IMO regulations acted as a demand-pull policy raising the payoff of successful environmental innovation of which MSSs are a fitting example (Makkonen and Repka, 2016). Therefore, although the importance of technology and demand should be considered when discussing the development of the TSI of MSSs, it was IMO regulations that set things in motion for its evolution: although discussions on the possibilities of MSSs as an abatement method had started already in 1997 (when IMO adopted the MARPOL Annex VI), the actual development work for MSS started only after IMO regulations came into force (Figure 6). Thus, the second function (*influence on the direction of search*) of the TSI of MSS was mainly induced by regulatory pressures: it should be underlined that without IMO regulations it would have been unlikely that significant interest from companies to invest on R&D to develop MSSs nor market demand from shipping operators towards MSSs for cutting down their SO_X emissions would have emerged on a voluntary basis.

High growth phase – The economic operability of MSSs was also improved via national support systems. The forms of national support often involve technology-push policies aimed at reducing the costs of innovating via government backing for loans and direct financial support for producing more environmentally friendly products (Makkonen et al., 2013; Makkonen and Repka, 2016). Therefore, for example the Finnish government was eager to support MSSs as an environmental innovation – it decided to subsidize MSS installations for Finnish ships (Bloor et al., 2014; Bergqvist et al., 2015). However, all vessels were not judged to “need” this subsidy since in many cases the installation was deemed economically feasible without any government support. Many shipping operators have, therefore, criticized these developments and instead turned to implementing alternatives (especially in times of low fuel prices) which require lower investments (but can have higher operating costs) – mainly to modify their engines for LFO. Still, it was this policy mix of (environmental) demand-pull and technology-push policies that supported the development of MSSs as a TSI focused around an environmental innovation.

Keeping in mind that the EU and many national governments have also supported MSS manufacturers in their R&D activities, it can be stated, related to the sixth function (*resource mobilization*), that the TSI of MSS has been relatively successful in attracting financial capital. Moreover, the support that MSSs have received is a sign of the fifth function (*legitimation*) of the TSI of MSSs: MSSs have been approved as an abatement method to meet IMO regulations. Additionally, classification societies play a role in this function, since they act as the monitoring organizations awarding individual MSS manufacturers with certificates to legitimate the feasibility of their products.

<Figure_6>

4.2.5 The technological systems of innovation perspective

As shown in Figure 2, the links between the SSI and TSI frameworks are manifold and they manifest through the functions of the TSI of MSSs:

1. Knowledge development and diffusion: covers the knowledge base of the MSS manufacturers (technological regime). Particularly, the way they have utilized their earlier experience on scrubber technologies in other sectors than shipbuilding.
2. Influence on the direction of search: has been guided first by the available technologies applied in other sectors (technological regime), second by the articulation of interest to fit MSSs into vessels from the shipping companies (market demand), and third (and most importantly) by the regulatory pressures set by IMO documents (public policy) mandating more stringent limits to shipping emissions and the timeframe to meet these requirements.
3. Entrepreneurial activity/experimentation: is related to both the MSS manufacturers that turned their knowledge on scrubber technologies into concrete action through the first prototypes of MSSs (technological regimes) and shipping companies that acted as the first experimenters to install pilot MSSs into their vessels (market demand).
4. Market formation: followed the evolution of market demand (that is, via the increase in the number of commercial orders for MSS installations) from a niche market into a more voluminous bridging market that emerged when the implementation date of the IMO regulations was at hand.
5. Legitimation: has been fulfilled by the above-mentioned acceptance from the shipping companies to utilize MSSs as an abatement method (market demand), but also from the acceptance by the relevant institutions (public policy); i.e. IMO in accepting MSSs as an abatement method, the EU and national governments in supporting their development and installation, and the relevant classification societies in monitoring the feasibility of MSSs in reducing SO_X emissions.

6. Resource mobilization: has been accomplished first via the human capital – that had the knowledge to combine expertise on scrubber technologies to fit the specific needs of shipping – inherent in the MSS manufacturers (technological regime), second via the partnerships of MSS manufacturers and shipping operators to test the first pilot projects (market demand), and third via successful (lobbying) activities to fund the development and testing of MSSs, and their (retro)fitting into vessels (public policy).
7. Development of positive externalities: is most evident in the way that the TSI of MSSs has been able to increase its economic impact – resulting e.g. in positive knowledge spillovers (technological regime) – via increasing demand that has led to the growth of established actors, but also to the emergence of new MSS manufacturers (e.g. in China).

5 CONCLUSIONS

This paper has focused on MSSs as an example of environmental innovation by bridging the SSI and TSI frameworks and by mapping the development and evolution of the TSI of MSSs into a feasible method for shipping emission abatement. The main empirical conclusions of the paper can be summarized as follows:

> For MSSs to emerge as an environmental innovation, existing technology in electric power, clean tech, and manufacturing industries was needed to constitute the technological regime on which product development was based. The demand rose gradually as the date for IMO regulations closed in due to necessity and government support for adopting this technology. However, in the end it can be stated that in the case of MSSs the initial and most powerful impetus for the technology has come from environmental policies restricting sulfur emissions. This created a strong belief in future growth potential for MSSs. The development has been further promoted with policies for supporting MSS manufacturers in their R&D and shipping operators in installing MSSs on their vessels. In short, the existing technological regime and emerging markets played a role in the development of this new technology, but MSSs can mostly be seen as a response to policy measures – as has been commonly the case with environmental innovation (Köhler et al., 2013; Makkonen and Repka, 2016). Thus, IMO regulations paved the way for MSSs to develop into a TSI. The required technology had existed on land for decades, but companies were not willing to take advantage of this technology before the announcement of the (upcoming) IMO regulations. Similarly, there were only a few green consumers willing to test the technology – the demand for MSSs did not really grow until the implementation of IMO regulations was almost at hand. Therefore, the role of policies in the creation of the TSI of MSSs was of pivotal importance. This is likely to be the case with other TSIs centered on environmental innovation.

These points bring forth a number of interesting implications. From a theoretical and analytical point of view the relevance of this paper has to do with its efforts in combining TSI and SSI perspectives into a coherent description of the development and evolution of an environmental innovation. As was shown here, taken together these aspects complement each other and function as a useful framework for this type of explorative study design. In terms of policy implications, it can be underlined that, firstly, environmental regulations can induce innovation. Secondly, governmental support for R&D to produce these innovations is extremely important, since market demand alone might not be enough – prior to the enforcement of environmental regulations – to convince manufacturers to develop new environmentally sound technologies. Thirdly, in cases where innovation is induced by environmental regulations, governmental support is also needed for its adoption and implementation, since the higher initial purchasing prices commonly complicate the assessment of the economic feasibility of environmental innovation, compared to established technologies, leading to resistance to adopt or implement them. It should be guaranteed that the support is significant enough for it to make sense for the customers (in the case of MSSs the underdeveloped market for the technology has been the foremost blocking mechanism of the TSI) to start using the new technologies, rather than choosing other (environmentally inferior) alternatives, abandoning the field, or moving to other regions with less stringent regulations.

This paper opened up ways to understand the potential of integrating the SSI and TSI approaches. The empirical parts of the paper rely on a single case. Therefore, in future studies more empirically detailed approaches with both quantitative and qualitative methods are needed. In addition, comparative studies on other TSIs based on environmental innovation potentially broaden our understanding of the complex relationships between national and international regulations, various conceptions of innovation systems, the environment, and the economy. Since MSS manufacturers are already facing competition from alternative fuel sources, while it is also likely that new alternative abatement methods will emerge in the future, the renewal of shipping equipment will remain a relevant field for future environmental innovation studies.

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HIGHLIGHTS:

- Sectoral and technological systems of (environmental) innovation are bridged
- Environmental regulations led to the development of marine scrubber systems
- Knowledge from other sectors was needed for the technological regime
- Market demand from early experimenters was important to the evolution of the system

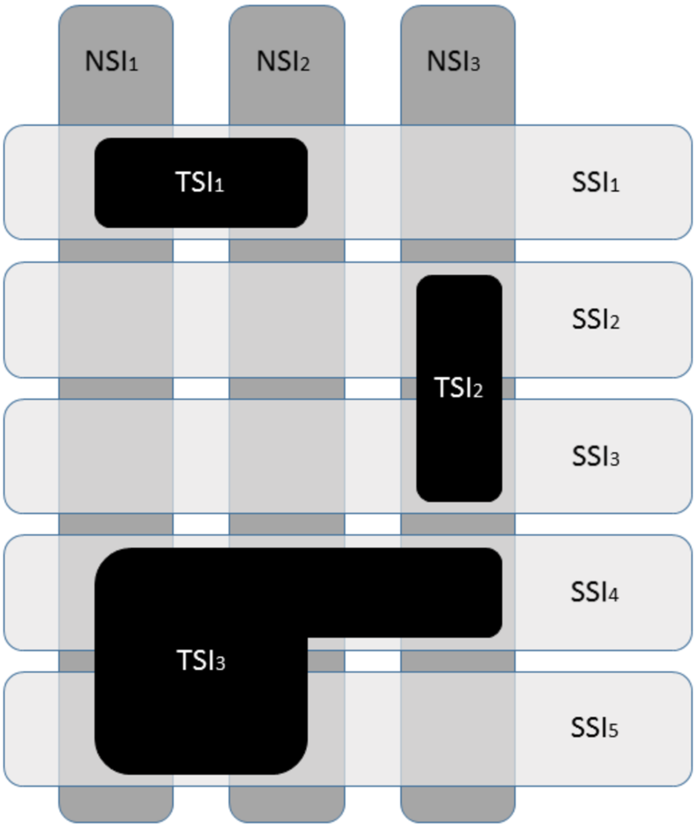


Figure 1. Geographical (national systems of innovation, NSIs) and sectoral (sectoral systems of innovation, SSIs) boundaries of potential technological systems of innovation *(TSIs). Modified from: Markard and Truffer (2008).*

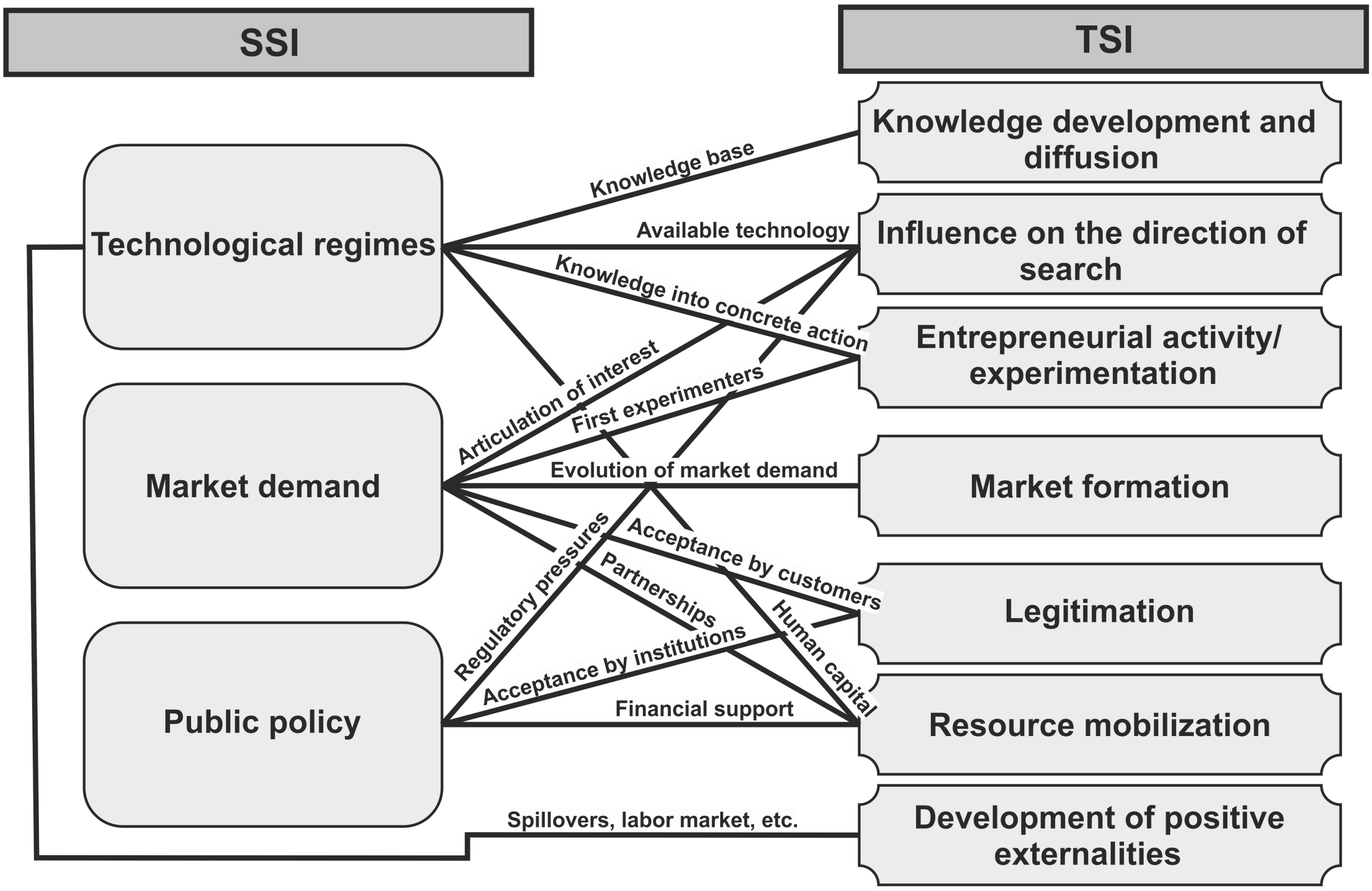


Figure 2. Interdependencies between the building blocks of sectoral systems of innovation (SSI) and the functional patterns of technological systems of innovation (TSI). Source: Authors.

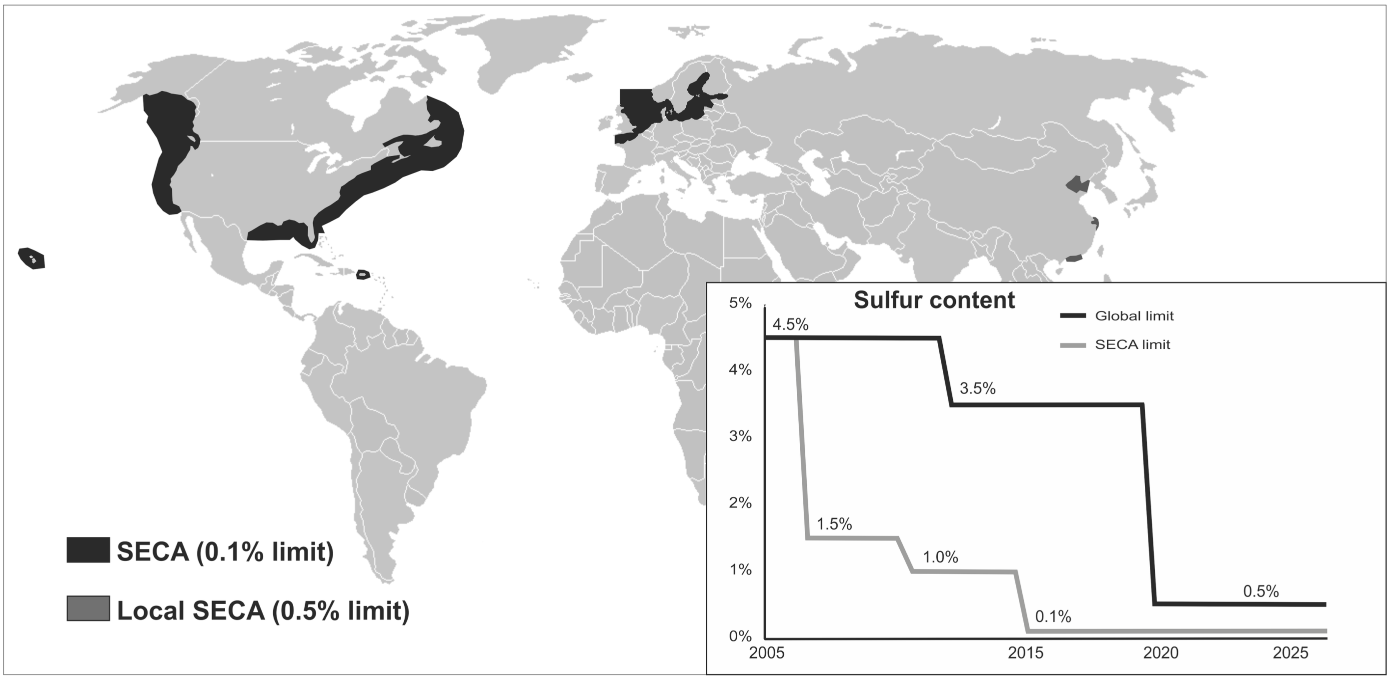
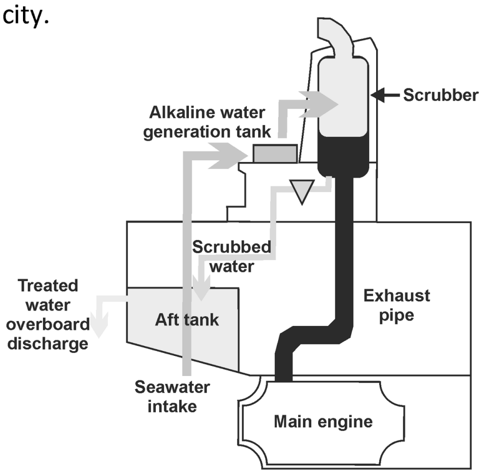


Figure 3. The geographical and regulatory aspects (sulfur content in bunker fuel) of Sulphur Emission Control Areas (SECAs). Source: Authors; based on data from Makkonen and Repka (2016).

Wet scrubbers

Wet scrubbers use water to “wash” away the sulfur from the fuel gases:

A) In an open system, seawater is used for purification. The water is then pumped back into the sea. The system is more efficient in sea areas with high salt levels and it also needs marine environments with high salinity and alkalinity to discharge the used water for it to neutralize. The scrubber is mounted near the chimney but it also requires space for water treatment systems and pumps. Thus, it occupies a lot of space, which reduces the cargo capacity.



B) The closed system uses freshwater to clean emissions and it is, thus, not dependent on the salt level of the sea. The waste generated is collected in special tanks and the system is thus suitable in fragile, shallow coastal waters. The waste is then “unloaded” in specialized port facilities. Scrubber waste is an expensive waste fraction. In many ports, vessels will be charged per amounts of scrubber waste discharged. The system requires more space on board than the open system due to the need to install extra tanks for chemicals and waste.

C) There are also hybrid systems that can use both freshwater and seawater depending on the sea area that the ship is operating in.

Dry scrubbers

Dry scrubbers use chemicals – for example, calcium hydroxide pellets – in the purification process. The unit itself weighs approximately 250 to 300 tons (including 150 to 200 tons of pellets), while the pellets last about 10–14 days before they need to be replaced in a port. This results in a likely need to reduce cargo space to house the unit.

Figure 4. Wet and dry marine scrubber systems. Source: Authors; based on data from Bergqvist et al. (2015) and Svaetichin and Inkinen (2017).

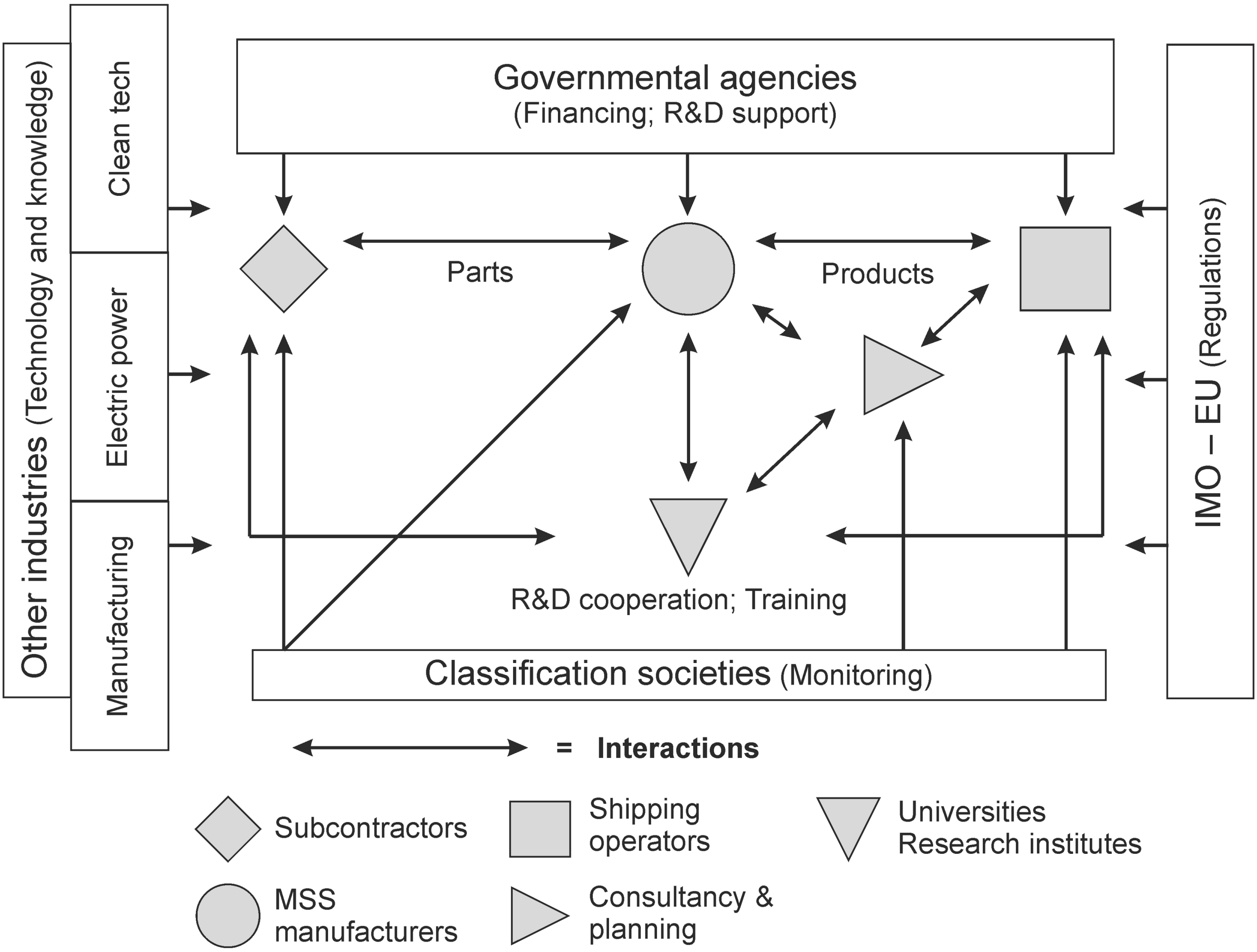
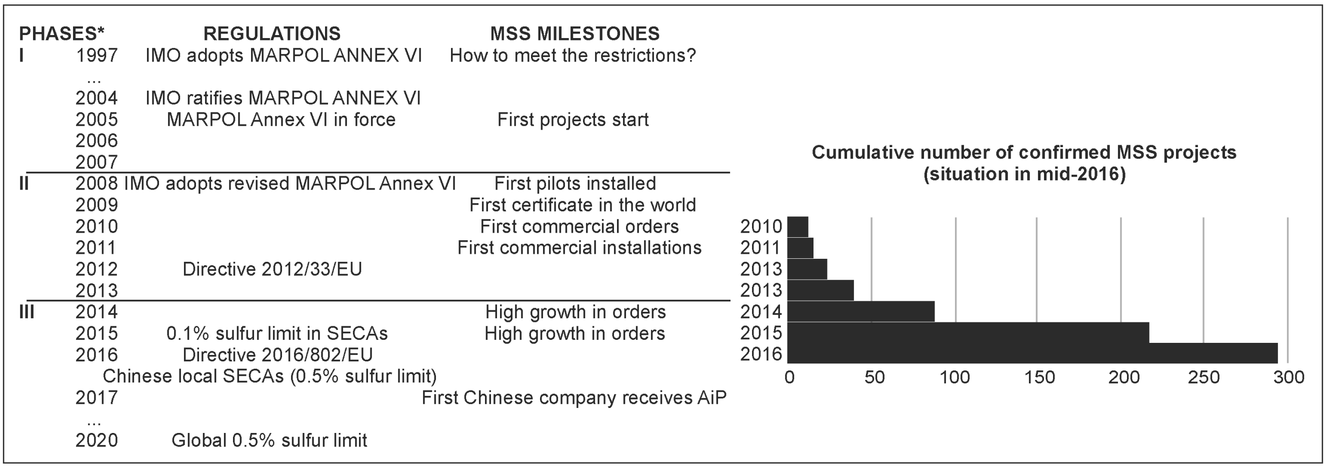


Figure 5. The network of actors involved in the development and production of marine scrubber systems (MSS): agents, interactions and sectors involved (EU = European Union; IMO = International Maritime Organization; R&D = research and development). Modified from: Karvonen et al. (2016).



PHASES*		REGULATIONS	MSS MILESTONES
I	1997	IMO adopts MARPOL ANNEX VI	How to meet the restrictions?
	...		
	2004	IMO ratifies MARPOL ANNEX VI	
	2005	MARPOL Annex VI in force	First projects start
	2006		
	2007		
II	2008	IMO adopts revised MARPOL Annex VI	First pilots installed
	2009		First certificate in the world
	2010		First commercial orders
	2011		First commercial installations
	2012	Directive 2012/33/EU	
	2013		
III	2014		High growth in orders
	2015	0.1% sulfur limit in SECAs	High growth in orders
	2016	Directive 2016/802/EU Chinese local SECAs (0.5% sulfur limit)	
	2017		First Chinese company receives AiP
	...		
	2020	Global 0.5% sulfur limit	

*Figure 6. Summary of environmental regulations affecting the milestones of marine scrubber system (MSS) development and their demand. Source: Authors; based on data from Henriksson (2013) and DNV LG (2016). *Note = I) Early development phase; II) Moderate growth phase and III) High growth phase.*