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MarPEM: An agent based model to explore the effects of policy instruments on the transition of the maritime fuel system away from HFO

G. Bas [a,*], K. De Boo [b], A.M. Vaes-Van de Hulsbeek [b], I. Nikolic [a]

[a] *Faculty of Technology, Policy and Management, Delft University of Technology, P.O. Box 5015, 2600 GA Delft, The Netherlands*
[b] *Port of Rotterdam, P.O. Box 6622, 3002 AP Rotterdam, The Netherlands*

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ABSTRACT

To lower the emissions of deep sea shipping, policymakers aim to decrease the use of heavy fuel oil (HFO) as a maritime fuel. Multiple alternatives for HFO exist, but despite new regulations, their use is still limited. To stimulate shipping companies to replace HFO by one of the alternatives, policymakers can use a variety of policy instruments. In this paper, we present a comprehensive system perspective of the maritime fuel system and agent-based model (MarPEM) that can be used to study the effects of policy instruments on the transition away from HFO. In contrast to existing studies on reducing maritime emissions, our system perspective captures the relations and dynamics between different components of the maritime fuel system. Thereby, it can account for the feedback and non-linear dynamics in the system. We illustrate the use of MarPEM to assess the effect of three policy instruments that each influence the maritime fuel system differently. The outcomes of the experiments are in line with previous studies and the opinion of industrial experts. The model is thus a valid representation of the maritime fuel system. By presenting a sufficiently detailed representation of the marine fuel socio-technical system, listing clear and detailed assumptions, and publishing the source code, future studies can use this work as basis to study the effects of other policy instruments. Thereby, this research enables future detailed studies of the maritime fuel system's transition.

1. Introduction

The continually increased globalisation of the economy has led to a growing demand for transport. Over 80% of this transport is carried out by sea-faring vessels (United Nations Conference on Trade and Development (UNCTAD), 2015), of which the vast majority use heavy fuel oil (HFO) for their propulsion (Corbett and Koehler, 2003). Together, those vessels emit around 3% of global CO_2 emissions, 15% of global NO_x emissions, and 13% of global SO_x emissions (International Maritime Organization (IMO), 2014), exacerbating a range of environmental issues.

To reduce the emission of sulphur oxides (SO_x), recently introduced regulations prohibit the use of fuels with a sulphur content above 0.10% in the coastal waters of the United States and North-West Europe. Outside those sulphur emission control areas (SECAs), the sulphur content of maritime fuels is currently limited to 3.50%, but is scheduled to be lowered to 0.50%

* Corresponding author.
E-mail address: G.Bas@tudelft.nl (G. Bas).

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in 2020 (IMO, 2015). HFO has a sulphur content of 2.7% and thus can currently still be used outside the SECAs (IMO, 2014). However, after 2020 shipping companies need to start looking for alternatives to HFO. A variety of those alternatives have been identified, such as liquefied natural gas (LNG), marine gas oil (MGO), or scrubbers to clean the emissions. However, the adoption of those alternatives has been very slow (Moirangthem, 2016). For instance, as of July 2015, there are 65 LNG-powered vessels in operation and 79 are scheduled to become operational in the coming years (DNV-GL, 2015): only 0.3% of the total of 55,000 sea vessels (IMO, 2012).

There are multiple factors underlying the limited replacement of HFO as maritime fuel (Wang and Notteboom, 2014). One of those factors is that the infrastructure to supply the alternative fuels is less developed than that to supply HFO. This is especially an issue for LNG, which needs to be stored and distributed at temperature below −162 °C and thus requires special infrastructure (Wang and Notteboom, 2015). While this infrastructure is not developed, shipping companies will not invest in LNG-powered vessels; and while there are no LNG-powered vessels, no fuel supplier will invest in the infrastructure (Danish Maritime Authority, 2012): a classic example of a chicken-and-egg problem (Adamchak and Adede, 2013). Furthermore, Wang and Notteboom (2014) identified factors related to the regulatory framework, the economic viability, the technical feasibility, and the public-social awareness.

Policymakers have a variety of means to mitigate those limiting factors and stimulate the transition of the maritime fuel system away from HFO. For instance, subsidising the retrofitting of vessels to use another fuel, fining offenders of the emission regulations, or stimulating the availability of alternative fuels in ports. However, the effects of those policy instruments on the fuel adoption in the maritime fuel system are in many cases unknown.

So far, there have been a number of studies that assessed means to reduce the emissions of maritime transport. The majority of those studies compared the economic and environmental performance of different maritime fuels and propulsion technologies (e.g., Brynolf et al., 2014; Eide et al., 2013; Jiang et al., 2014; Ren and Lützen, 2015), studied the barriers for vessel owners to improve their energy efficiency (e.g., Johnson et al., 2014; Jafarzadeh and Utne, 2014), or researched the economics of the required LNG bunker infrastructure (e.g., Danish Maritime Authority, 2012; Harperscheidt, 2011; Semolinos et al., 2011). All those studies have in common that they assess the (economic or environmental) micro-performance of a certain technology or fuel isolated from the rest of the maritime fuel system. While this work is very important, it does not take into consideration that LNG adoption emerges from behaviours and interactions within the elements of maritime fuel system over time. So, in order to assess the dynamics of the transition away from HFO, a study of policy instruments needs to consider the multitude of maritime fuel system elements and their interactions.

In this paper, we present a comprehensive system perspective of the maritime fuel system that can be used to study the effects of policy instruments on the transition away from HFO. This system perspective is implemented in an agent-based model: Maritime Fuel Policy Exploration Model (MarPEM). This model allows us to study the possible development of the maritime fuel system and the emergence of a transition for a variety of policy instruments. MarPEM represents the maritime fuel system as a set of heterogeneous agents that decide autonomously and interact with each other and their environment (Shalizi, 2006). Agent-based models have been used often to study how the transition of a system may be stimulated – such as the transition to other automotive fuels or the adoption of plug-in hybrid electric vehicles (Van Vliet et al., 2010; Eppstein et al., 2011). To demonstrate the functioning and illustrate the use of MarPEM, we apply it to explore the effect of three policy instruments that each influence the maritime fuel system in a different way. Thereby, those experiments show that MarPEM can be used to assess a variety of policy instruments and thus can be applied in future studies.

2. The maritime fuel system

The system perspective that we propose for this study considers a much wider system scope than is common in transition studies. The goal is to capture the feedbacks between different parts and the subsequent non-linear system behaviour (Bar-Yam, 2011). By capturing that non-linear system behaviour, we can obtain a thorough understanding of the consequences of studied policy instruments. As a consequence, the system perspective is fundamental to technology change and sustainability transition research (Ulli-Beer, 2013).

The maritime fuel system (covered by the system perspective) comprises the physical assets that produce, distribute, and consume fuels, as well as the organisations that interact with each other to arrange the physical handling of those fuels. This system is a socio-technical system, and thus can be described as a system of tightly interwoven technical and social subsystems (Hughes, 1987; Ottens et al., 2006). Fig. 1 gives an overview of the system's social and technical systems, which are discussed in further detail in this section.

2.1. Technical system

The technical system consists of the physical entities that handle maritime fuels and are connected to each other via the flow of those fuels. *Vessels* are the entities that consume maritime fuel to transport cargo between ports. Vessels use different propulsion technologies, which determine the type of fuel they use, their fuel efficiency, and their emissions (Danish Maritime Authority, 2012).

The vessels bunker their fuel in a port via *distribution infrastructure*, which can consist of bunker barges, trucks, or pipelines (De Buck et al., 2011). To ensure sufficient availability, maritime fuels are temporarily stored in *bunker storage tanks* that