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Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision making approach

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ABSTRACT

The use of alternative energy sources instead of HFO has been recognized as a promising way for reducing emissions from shipping and promoting the development of green shipping. However, it is usually difficult for the decision-making to select the best choice among multiple alternative marine fuels. In order to address this, a complete criteria system for sustainability assessment of alternative marine fuels was firstly established, and a fuzzy group multi-criteria decision making method has been developed to rank the alternative marine fuels by combining fuzzy logarithmic least squares and fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution). Fuzzy logarithmic least squares method has been employed to determine the weights of the criteria for sustainability assessment, and fuzzy TOPSIS was employed to determine the sustainability order of the alternatives. An illustrative case with three alternative marine fuels including methanol, LNG and hydrogen has been studied by the proposed method, and hydrogen has been recognized as the most sustainable scenario, follows by LNG, and methanol in the descending order. The results show that the proposed method is feasible for prioritizing the alternative marine fuels; it also has the ability to help the decision-makers to select the most sustainable option among multiple marine fuels.

1. Introduction

The increase of the amount of goods transported by ships has caused an increase in the amount of fuel consumption (El Gohary and Seddiek, 2013). The principal exhaust gas emissions from shipping, i.e. CO_2 (Carbon Dioxide), NO_x (Nitric Oxides), SO_x (Oxides of sulfur), CO (Carbon Monoxide), hydrocarbons, and PM (particulate matter), have significant impact on air quality (Eyring et al., 2005). After adopting the regulations for the Prevention of Air Pollution from Ships (Annex VI), many alternative marine fuels have been recognized as promising scenarios to reduce air pollution from ships (Adamchak and Adede, 2013). Meanwhile, the use of renewable or green energy sources which can substitute the traditional fossil fuels, especially the heavy fuel oil HFO(HFO), were recognized as promising way for achieving green shipping with the increase of the perceptions and attentions of people on environment protection and air quality improvement (Welaya et al., 2011). Laugen (2013) found that liquefied natural gas LNG (LNG) performs marginally better than HFO in life cycle environmental

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impacts, and it shows that LNG produces 92% less emission than HFO, and the total emissions of LNG and HFO are 127 CO_2-eq/ton km and 130.13 CO_2-eq/ton km, respectively.

Besides LNG, there are also some other renewable or green energy sources which can be used as power of ships, including biodiesel, wind power, liquefied biogas, bio-methanol, and nuclear power. However, different alternative marine fuels have different economic performances, environmental impacts, and social effects. The decision-makers usually have to face several conflicting criteria when choosing the most sustainable marine fuel which has the best integrated performances on economic, environmental, social and technological aspects among multiple alternatives. For instance, methanol is a promising environmental-friendly fuel for shipping; however, the current price of methanol is relatively high which seriously hindered the development of methanol propulsion (Lundgren and Wachsmann, 2014). These are many studies focusing on comparing different alternative marine fuels, and most of these studies aim at comparing the environmental performances of different alternative marine fuels for choosing the most environmental-friendly one. For instance, Brynolf et al. (2014) employed life cycle assessment tool to investigate the environmental impacts of marine fuels including LNG, liquefied biogas, methanol and bio-methanol, and the results shows that the use of liquefied biogas and bio-methanol can reduce the climate change potential. Bengtsson et al. (2011) carried out a life cycle environmental impact investigation of four fossil fuels for marine propulsion including HFO, marine diesel oil (MDO), marine gas oil (MGO), and LNG. Øberg (2013) evaluated the life cycle impacts of fuel choice for different marine vessels and their typical operations. Bengtsson (2011) investigated the life cycle environmental impacts of various alternatives to comply with upcoming environmental regulations, including HFO with a scrubber, marine gas oil with selective catalytic reduction, LNG, and synthetic diesel with selective catalytic reduction, etc. Welaya et al. (2011) compared fuel cell and some other marine electric power generation with the considerations of efficiency over a wide range of loads, response to load changes, life, noise, power range, and various emissions. Andersson (2017) has assessed the "well to propeller" energy input and GHG emissions for a number of present and proposed marine fuels including fossil and renewable energy sources. However, the comparison of different marine fuels in environmental impacts or some other issues cannot directly tell the decision-makers/stakeholders which the most sustainable scenario is when facing multiple marine fuel options. Accordingly, Deniz and Zincir (2016) used Analytic Hierarchy Process (AHP) to prioritize methanol, LNG and hydrogen as the alternative marine fuels. Ren and Lützen (2017) developed a novel multi-criteria decision-making method that combines Dempster-Shafer theory and a trapezoidal fuzzy analytic hierarchy process for alternative energy source selection under incomplete information conditions. Guerra and Jenssen (2014a, 2014b) developed a multi-criteria decision analysis (MCDA) model based on AHP for Norwegian maritime sector, marine diesel oil (MDO) and LNG (LNG) have been studied by the proposed model, and the results show that LNG is a more preferred solution compared with MDO. Bulut et al. (2015) improved the applicability of the fuzzy-AHP method by using the rotational priority investigation to rank six alternative marine engines. These studies are of vital importance for the decision-makers/stakeholders to select the best option among multiple alternatives. However, there are still some research gaps which should be filled: (1) The lack of considering the three pillars of sustainability simultaneously when selecting the best or the most suitable marine fuel among multiple alternatives; (2) multiple stakeholders should participate in sustainability assessment of alternative marine fuels to achieve group and democratic decision-making; (3) the convenient method should be developed for the decision-makers/stakeholders to express their opinions and preferences on the relative importance of the criteria for sustainability assessment and the relative performances on the alternative marine fuels with respect to each criterion. Accordingly, sustainability should be incorporated for the selection of marine fuels, and it has been measured as a goal of the alternative marine fuels in this study. As for quantifying sustainability, triple bottom line (TBL) can incorporate not only the traditional measures of profits and return on investment, but also shareholder value to include environmental and social dimensions (Hall, 2011). Thus, sustainability assessment usually needs to measure three pillars including economic, environmental and social categories. As for the sustainability of alternative marine fuels, there is not a unique criteria system, but there are various studies about sustainability assessment of fuels. For instance, Zhou et al. (2007) employed four indicators including economy indicator (life cycle cost of fuel), environment indicator (global warming potential), energy indicator (the net energy from a fuel) and renewability indicator (non-renewable resource depletion potential) to measure the sustainability of fuels. Tzeng et al. (2005) employed eleven criteria in four aspects including social, economic, technological, and transportation to assess the sustainability of alternative-fuel buses for public transportation. Zhou et al. (2012) developed a new indicator, CNER (Cost of Net Energy taking into account the Renewability) for life cycle sustainability assessment of fuels by incorporating net energy (NE) output, external cost to society of emissions, total production costs, and the renewability of fuels. Gnanapragasam et al. (2010) used three sustainability dimensions (ecological, sociological and technological) and ten indicators for each dimension for measuring the sustainability of hydrogen fuel. In order to fill above-mentioned gaps, fuzzy logarithmic least squares method and fuzzy TOPSIS have been combined to assess the sustainability of different marine fuels in this study.

The residual parts of this study have been organized as follows: Firstly, Section 2 provided the models for sustainability assessment of alternative marine fuels, including the criteria for sustainability assessment, fuzzy logarithmic least squares for weights determination, and fuzzy TOPSIS for ranking the alternatives. Then, an illustrative case has been studied by the proposed method in Section 3, the results have also been validated, and sensitivity analysis has also been carried out to test the robustness. Finally, this study has been concluded in Section 4.