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Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study

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HIGHLIGHTS

- Resources, emissions and impact from manufacture to end of life were estimated.
- Operating diesel gensets and disposing metallic scrap were significant processes.
- Correlations between fuel consumption and impact categories were identified.
- The influence of the end of life scenarios on ecotoxicity potential was studied.
- Environmental benefits of the hybrid system were compared and verified.

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ABSTRACT

Marine transport has been essential for international trade. Concern for its environmental impact was growing among regulators, classification societies, ship operators, ship owners, and other stakeholders. By applying life cycle assessment, this article aimed to assess the impact of a new-build hybrid system (i.e. an electric power system which incorporated lithium ion batteries, photovoltaic systems and cold-ironing) designed for Roll-on/Roll-off cargo ships. The study was carried out based on a bottom-up integrated system approach using the optimised operational profile and background information for manufacturing processes, mass breakdown and end of life management plans. Resources such as metallic and non-metallic materials and energy required for manufacture, operation, maintenance, dismantling and scrap handling were estimated. During operation, 1.76×10^8 kg of marine diesel oil was burned, releasing carbon monoxide, carbon dioxide, particulate matter, hydrocarbons, nitrogen oxides and sulphur dioxide which ranged 5–8 orders of magnitude. The operation of diesel gensets was the primary cause of impact categories that were relevant to particulate matter or respiratory inorganic health issues, photochemical ozone creation, eutrophication, acidification, global warming and human toxicity. Disposing metallic scrap was accountable for the most significant impact category, ecotoxicity potential. The environmental benefits of the hybrid power system in most impact categories were verified in comparison with a conventional power system onboard cargo ships. The estimated results for individual impact categories were verified using scenario analysis. The study concluded that the life cycle of a new-build hybrid power system would result in significant impact on the environment, human beings and natural reserves, and therefore proper management of such a system was imperative.

1. Introduction

Among all transport modes, marine transport has been predominant. It enabled more than 80% of merchandise trade globally [1]. The business, by its very nature, was complex. It affected and was affected by

- legislation e.g. Marine Pollution (MARPOL) Annex VI *Regulations for the Prevention of Air Pollution from Ships* and Energy Efficiency Design Index (EEDI) which were enforced by International Maritime Organisation (IMO),
- economics e.g. capital investment of technologies and fuel cost,
- technologies e.g. choice, system designs and vessel types, and
- operation e.g. efficiency, sailing routes and speeds.

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The business involved a wide range of stakeholders including but not limited to ship owners, operators, builders, classification societies, authorities, regulators and researchers. In all circumstances, energy efficiency and technologies were at the core of research and development. The scientific findings were crucial as they could offer insightful information to the stakeholders and assist their decision making.

A number of research areas have already been explored. For instance, the influence of EEDI on future propulsion system designs for liquefied natural gas carriers was investigated by [2]. Based on the operational data, energy efficiency of feeders was evaluated by [3] which took sailing speeds, cargo capacity and time spent in port and at sea into account. Using a life-cycle energy management tool, energy efficiency of container ships was estimated by [4] which considered configuration designs and operational profiles. Based on the real-time operational profiles of two relevant ships, the potential of improving energy efficiency via shorter waiting time in port was explored by [5]. An artificial neural network (ANN) was applied by [6] in developing a model for fuel consumption prediction to support decision making for energy efficient operation. A framework was developed by [7] to assist ship owners in breaking down barriers to energy efficiency enhancement. Fuel consumption required for crane operation which involved the use of a battery, a diesel generator and a control system was estimated by [8].

In relation to prime mover technologies, diesel engines have been broadly researched to cover different aspects. Combustion models were developed for 2- or 4-stroke engines to analyse soot formation [9], nitrogen oxides (NO_X) formation and the use of exhaust gas recirculation (EGR) [10], effect of variation in engine loads [11], pilot injection for efficiency improvement and NOx reduction [12], scavenging flow and temperature distribution in the piston crown [13] as well as characterisation of particulate matter (PM) at various engine settings [14]. In addition, models were also developed to evaluate engine performance at slow steaming conditions [15], various sailing scenarios [16] and based on a zero-dimensional approach [17]. The concept of a multidimensional model which could be used as an engine diagnostic tool was proposed by [18].

A search for optimisation and advancement in technologies have been stimulated. This included waste heat recovery (WHR), fuel cells, wind propulsion and cold-ironing, to name a few. For example, operational (in terms of business route, ship trim, hull, propeller and engine performance), technical (including propeller programming, fuel slide valves, oil consumption and retrofit) and commercial (such as slow steaming, speed and fuel consumption) optimisation tools were reviewed by [19]. Based on a holistic approach, advanced computer-aided techniques were investigated by [20] for ship design optimisation. Sailing speed optimisation for ships that transited across Emission Control Areas (ECAs) was investigated by [21]. Focussing on WHR, the optimised thermodynamic and economic performance of an organic Rankine cycle (ORC) system was investigated by [22]. Covering fundamental principles, technical designs and economic aspects, WHR technologies were reviewed by [23]. Cooling systems powered by waste heat absorption and vapour compression cycles respectively were modelled and compared by [24]. Two propulsion options for ferries and Roll-on/Roll-off (RoRo) cargo ships, i.e. a dual fuel engine employing a WHR system and a conventional diesel engine were compared by [25] from technical and economic perspectives. Focussing on a diesel engine which integrated a WHR system, different optimisation possibilities that considered various control variables were studied by [26]. Marine power system designs which employed various types of fuel cells were presented by [27]. A marine trigeneration system which incorporated diesel generators, a solid oxide fuel cell, a gas turbine and an absorption heat pump was proposed by [28]. In addition, the optimal sizing method for a marine power system that integrated diesel engines, PV and battery systems under different operating conditions was proposed by [29]. Wind propulsion technologies including Flettner rotors and towing kites were modelled by [30] in addition to a hard sail study reported by [31]. For cold-ironing technologies, the shore-side design and control aspects were investigated by [32], electrical characteristics of the installation were examined by [33] and social-economic benefits were addressed by [34]. All these studies shared a common vision i.e. innovative technologies and techniques could address technical challenges and offer solutions to mitigate the environmental impact caused by maritime business, which in turn could protect the environment, society and natural reserves from further damage, as implied in [35].

Legislation, research and innovative development relevant to maritime business have been driven by increasing global concern over the environmental sustainability of marine transport. Marine transport was perceived to be more environmentally friendly than other modes *per unit of cargo shipped and distance travelled*. Still, its contribution to global emissions has been continual. Marine transport contributed, for instance, 2.1–2.2% of global carbon dioxide (CO_2) and CO_2-equivalent greenhouse gas (GHG) emissions in 2012, which accounted for 938 and 961 megatonnes respectively [36]. Some studies on marine transport primarily focused on emissions (in particular GHGs which were the major cause of climate change) without elucidating environmental issues, as implied by [37]. Relevant examples included [38–40]. The relationship between CO_2 emission and other factors such as ship types, sizes and the geographic setting was explored by [38]. To what extent efficient shipping could help reduce global CO_2 emissions was analysed by [39]. Emissions, cost and profit for the design of bulk vessels was investigated by [40]. A plausible explanation was that CO_2 emission had been adopted as a means to measure energy efficiency of marine power systems as in EEDI [2] whilst other GHG emissions were of lower magnitude and contributed less towards climate change. However, estimating GHG emissions and climate change was not enough as it did not present a full picture of the impact of marine transport on the natural environment. Climate change only represented one of the attributes of natural environment from a life cycle assessment (LCA) perspective, which was a common tool applied for environmental assessment. Any unnatural change in the attributes of human health and/or natural resources was indeed within the scope of environmental issues, which would affect the society directly and indirectly. Examples of environmental issues included

(i) ecotoxicity (for freshwater and marine aquatic, sediment and terrestrial ecosystems), acidification, eutrophication and photochemical oxidant formation in respect of natural environment;
(ii) noise, odour, ionising radiation, casualties, thermal pollution and human toxicity (such as respiratory, cancer and non-cancer effects) in relation to human health; and
(iii) freshwater consumption, depletion of fossil fuels and mineral resources relevant to natural resources.

Some impact categories were applicable to the marine context, as summarised in the supplementary material (Appendix 1) together with a brief description of the impact categories. In addressing the environmental issues, LCA has been practised in the marine context up to now, which covered software development, vessels, power technologies and systems, emission abatement techniques, fuels and waste, as summarised in Table 1. A scale of I–IV was adopted to describe how far the environmental impact of shipping or relevant technology has been assessed (from I which was for no coverage to IV which was for estimating more