Energy Conversion and Management 117 (2016) 305–318

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Investigating a conventional and retrofit power plant on-board a Roll-on/Roll-off cargo ship from a sustainability perspective – A life cycle assessment case study

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ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 10 March 2016
Accepted 11 March 2016
Available online 22 March 2016

Keywords:
Life Cycle Assessment (LCA)
Environmental impact
Resource consumption
Emission
Marine power plant
Retrofit

ABSTRACT

Following the enforcement of *MARPOL Annex VI Regulations for the Prevention of Air Pollution from Ships*, retrofitting conventional power plants with emerging technologies is seen as a means to promote sustainability of marine transport and comply with more stringent emissions legislation. However, a knowledge gap exists as the environmental performance of retrofit power plant solutions incorporating emerging technologies has not been examined using an integrated system approach based on Life Cycle Assessment. The purpose of this research was to investigate if integrating selected emerging technologies i.e. photovoltaic systems, lithium-ion batteries, cold ironing and power-take-off/power-take-in systems supplemented by frequency converters and variable frequency drives into an existing power plant would be to the advantage of a chosen ship type i.e. Roll-on/Roll-off cargo ships, from the perspectives of resource consumption and environmental burden. Using the power plant of an existing vessel as a case study, it was found that cast iron, steel, copper and aluminium were the four materials most commonly consumed during manufacturing phase i.e. 2.9×10^5 kg, 1.9×10^5 kg, 5.3×10^4 kg and 2.9×10^4 kg respectively. By burning 2.9×10^7 kg of heavy fuel oil and 2.3×10^8 kg of marine diesel oil during operation, 8.2×10^8 kg of carbon dioxide, 1.7×10^7 kg of nitrogen oxides, 6.1×10^6 kg of sulphur dioxide, 7.6×10^5 kg of carbon monoxide, 6.5×10^5 kg of hydrocarbon and 4.7×10^5 kg of particulate matter would be released. Over a projected 30-year period, emissions released to air and freshwater were found to be significant. Based on 3 characterisation methodologies, ecotoxicity potential, with 7–10 orders of magnitude, was identified as the most significant environmental burden. Consuming and storing resources had the least impact, operating diesel engines and auxiliary generators had a moderate impact, and disposing metallic waste had the highest impact. The research concluded that the environmental burden caused by a marine power plant was significant but retrofitting existing power plant with suitable emerging technologies could reduce a number of impacts by 4–7 orders of magnitude, as verified via scenario analysis. However, the system should be designed and managed with due care as the environmental benefits, such as lower fuel consumption, emission reduction and performance improvement in some environmental measures are always achieved at the expense of an increase in other detrimental impacts.

1. Introduction

Among all transportation modes, shipping is perceived to be environmentally friendly [1], in terms of total energy consumption and emissions. However, concern over the environmental impact of shipping is growing. In the late 1990s, deep sea storage of carbon dioxide (CO_2) released from marine power plants were investigated. For example, Golomb [2] estimated the environmental impact of CO_2 transport systems whilst Kildow [3] proposed a framework how to select the options based on legal and socio-political parameters. To address this challenge, recent research has extended to cover a wider scope. To estimate the contribution of shipping to global CO_2 emissions, Heitmann and Peterson [4] assessed global CO_2 reduction targets using marginal abatement cost curves developed for shipping and CO_2 abatement techniques. Based on emission data collected from ships, Westerlund et al. [5] characterised particulate matter (PM) in relation to particle size, mass, number of volatility. By taking account of ship movements, energy and environmental aspect, Wang et al. [6] applied a model

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http://dx.doi.org/10.1016/j.enconman.2016.03.032
0196-8904/

to estimate energy consumption and emissions released by ships within selected ports. Also, Moreno-Gutiérrez et al. [7] compared current methods used for estimating energy and emissions whilst Ushakov et al. [8] analysed the composition of exhaust released from marine fuel combustion. With exhaust samples, Winnes and Fridell [9] analysed the correlation between sailing mode and emissions. Meanwhile, Stevens et al. [10] investigated the relationship between marine technologies and legislation. Using environmental government mechanisms, Lun et al. [11] focused on the deployment of 'green' ship operations by shipping organisations.

For the vast majority of vessels, marine diesel engine power plants are the primary means of energy conversion and source of harmful emissions. Thus, a number of studies have focused on the correlation between diesel engine operation and emissions. For example, Uriondo et al. [12] explored how the temperature and pressure of charged air would affect nitrogen oxides (NO_x) emission whilst Grados et al. [13] attempted to reduce such emission via injection pressure correction. Meanwhile, Duran et al. [14] investigated how engine maintenance would affect NO_x and carbon monoxide (CO) emissions. In addition, Di Natale and Carotenuto [15] studied PM emission released by engines and possible reduction control strategies. Recovering waste heat from diesel engine exhaust via the application of novel cycles has been investigated. For example, Nielsen et al. [16] designed a combined steam and organic Rankine cycle deployed with a diesel engine, and Yang [17] analysed the efficiency and economic performance of a waste heat recovery system that deployed transcritical Rankine cycle. Although not as widely applied as diesel engine power plants, alternative prime movers employing various cycles have been reported. In this matter, Haglind [18] discussed the design of combined cycles, including combined gas and steam turbines, combined gas turbine electric and steam, and heat recovery steam generators. Haglind [19] extended the study by covering the implications of combined cycles, followed by a comparison of emissions released by gas turbines and diesel engines. Also, Romero Gómez et al. [20] investigated a boil-off gas reliquefaction system with cascade cycles designed for liquefied natural gas carriers.

To promote sustainability, emission reduction strategies proposed by the International Maritime Organisation (IMO) include the use of clean fuels, improved energy efficiency through better vessel design and effective operation, and the use of advanced technologies [21]. Technical strategic measures could include more efficient ship hulls, engines and propulsion systems, use of alternative fuels, emission abatement systems, cold ironing, photovoltaic systems, fuel cells and the use of sails. Operational strategies could include slow steaming, optimisation of speed, schedule and decision, weather routing, fleet planning. Market-based strategies could include a carbon levy and emission trading schemes. NO_x and/or sulphur dioxide (SO_2) abatement techniques have been discussed. To assist ship owners in selecting the most suitable abatement technique, Yang et al. [22] developed a generic methodology. Focussing on SO_2 abatement techniques, Ma et al. [23] analysed both energy and emissions released by marine fuels due to crude oil production, processing, distribution, consumption and scrubbing. To compare the use of marine gas oil and scrubbers, Jiang et al. [24] performed a cost-benefit analysis. From a legal perspective, Brynolf et al. [25] assessed alternatives that might comply with future requirements. Moreover, ship speed has been scrutinised from different angles. For instance, Psaraftis and Kontovas [26] reviewed speed models, taxonomy and relevant parameters for marine transport. In line with economic and environmental perspectives, Psaraftis and Kontovas [27] scrutinised the implications of speed reduction. To achieve optimum speed and fuel consumption at minimum cost, Kim et al. [28] proposed an algorithm for bunker fuel management. Whilst Fagerholt and Psaraftis [1] focussed on optimisation issues associated with fuel-switching, Fagerholt et al. [29] developed a model to assist ship operators in determining optimal sailing routes and speed. Likewise, optimal power flow for power systems have been proposed to offer a multi-objective solution. For example, Niknam et al. [30] developed a Shuffle Frog Leaping algorithm which took emissions and economic factors into account. The algorithm was extended and integrated with Particle Swarm Optimisation by Narimani et al. [31] to develop a hybrid algorithm. Furthermore, Niknam et al. [32] proposed a stochastic model which applied probability distribution functions to address uncertainties in different scenarios.

In addition, decision support tools have been developed in relation to retrofitting a cargo ship by (i) installing an exhaust gas scrubber or switching to low sulphur fuel, as investigated by Patricksson et al. [33] and (ii) connecting shaft generators to frequency converters, as proposed by Schøyen and Sow [34]. Also, Ölçer and Ballini [35] presented a decision-making framework which assessed the trade-off in all potential technologies and fuel sources for cleaner transportation. Meanwhile, Dimopoulos et al. [36] developed a process modelling framework for electric propulsion systems on-board large bulk carriers based on a system approach. Examples of advanced technologies have also been reported. For example, Livanos et al. [37] compared propulsions plants run by dual fuel and conventional diesel engines respectively – both incorporating waste heat recovery systems. In relation to cold ironing, Sciberras et al. [38] researched into electrical characteristics and implications on onshore power network. The work was supplemented by Coppola et al. as well as Ballini and Bozzo [39,40] – the former focused on design and control of 2 technology alternatives whilst the latter quantified the technology from a socio-economic perspective. Also, the use of sails to assist ship propulsion has been explored. Using wind tunnel tests and computational analysis, Izaguirre-Alza et al. [41] described the concept and analysed the performance. Based on performance and aerodynamic study, Li et al. [42] proposed cascade hard sails for potential applications in marine transport. Based on experimental approach, Majewska et al. [43] used sensors to measure strain and stress of a foremast.

Notwithstanding this recent focus, Cullinane and Bergqvist [44] concluded that shipping has largely escaped from environmental scrutiny if compared to other transportation modes. One way to verify this claim is to look at the number of Life Cycle Assessment (LCA) studies – a common tool used for environmental assessment – which have been applied to this transport mode. To date, LCA studies conducted have focussed on marine vessels, structures, fuels, power technologies, emission abatement, waste, software and framework development, as briefly reported here. To assess transport modes, Fet and Sørgård [45] developed methodologies that could be applied, followed by Johnsen and Fet [46] where a screening assessment was performed and Fet et al. [47] in which case studies on transport chain alternatives were presented. Building on the developed methodologies, screening assessment and case studies, Fet [48] presented an overview. Schmidt et al. [49] compared materials used for constructing the structure of an inland ferry i.e. steel and fibre composite. Whilst Bengtsson et al. [50] analysed the impact of fossil fuels, Bengtsson et al. [51] investigated the pathways towards biofuel applications. Focussing on fuel cell technologies and engines, Alkaner and Zhou [52] compared molten carbonate fuel cells with diesel engines; Strazza et al. [53] compared solid oxide fuel cells to diesel engines; and Strand and Aarskog [54] compared fuel cells, gas and diesel engines. In addition, Ma et al. [23] assessed emission abatement options whilst Zuin et al. [55] studied waste management options in port. Also, Jiven et al. [56] attempted to develop a tool that could be used during design phase. The work presented by Kameyama et al. [57,58] was related to one another in relation to LCA software development, as did Tincelin et al. [59] which offered a tool developed using commercial software. Whilst Princaud et al. [60]