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]

presented an eco-design demonstrator that incorporating environmental element, Basurko and Mesbahi [61] covered additional elements such as cost and safety aspects. Based on an in-depth review on methodology development, Ling-Chin et al. [62] developed an LCA framework for marine PV systems. Therefore, marine transport LCA case studies have been carried out but are relatively limited, considering the scale of activity and the diversity in vessel types, power plant designs, technologies, fuel types and sailing profiles.

Besides, some advanced technologies have been rarely applied for marine transport despite being more commonly implemented for onshore applications (e.g. photovoltaic (PV) systems) or road transport (e.g. energy storage) – both with a limited but increasing capacity. Neither has the integration of these emerging technologies in a retrofit/new power plant nor their environmental performance been studied using an integrated system approach. As such a knowledge gap exists. Knowledge was advanced in this research by applying LCA to investigate if integrating selected emerging technologies into an existing marine power plant would promote sustainability by adding environmental benefits to the chosen ship type i.e. Roll-on/Roll-off (RoRo) cargo ships. As the most widely applied propulsion type for cargo ships, diesel engine power plants rather than other alternatives were chosen. The study focused on retrofit instead of new-build design mainly because it has been envisaged as a green and competitive route for marine vessels that are built prior to the enforcement of *MARPOL Annex VI Regulations for the Prevention of Air Pollution from Ships*. The objectives were to (i) estimate resources, emissions and the environmental impact attributable to a marine power plant via LCA study; (ii) identify resource consumption and the causes of significant impact; (ii) understand the environmental implications of implementing the retrofit design and operating the power plant over its full life cycle by performing scenario analysis.

The methods applied in this study were reported in Section 2, covering the selection of technologies and reference ship, operational profiles, methodology and data sources. Section 3 presented the fundamental theory of emerging technologies under study and the LCA concept in accordance with ISO Standards. Results and discussion were reported in Section 4, detailing the phase-by-phase LCA study of the marine power plant, and followed by conclusions in Section 5.

2. Methods and description of the system under study

2.1. Selection of emerging power technologies and the reference ship

In principle, the retrofit design should be (i) innovative; (ii) within the interest of industry involved; (iii) making use of existing components on-board the reference ship; (iv) able to store and use surplus energy when required; and (v) improving operational performance during manoeuvring and transiting. Recent recommendations on emerging technologies that were considered included a hybrid design incorporating renewable sources e.g. solar as power augmentation for ships [63], energy storage, slow steaming [64] and cold ironing which could reduce total emission by up to 20% [65]. The retrofit system designed integrated these technologies with power-take-off/power-take-in (PTO/PTI, using shaft generators which were not in service on-board the reference ship), taking advantage of variable frequency drives (VFDs), and thrusters governed by frequency converters to eliminate stand-by mode and ensure high starting current, as illustrated in Fig. 1. The retrofit power plant design, which was the technical outcome of collaboration and discussion among consortium members and the ship owner (as credited in Acknowledgement) during the lifetime of the project in line with the established criteria, was anticipated to consume less fuel and release less harmful emissions. A RoRo cargo ship was selected as the reference ship since it had frequent transits and manoeuvring within Emission Control Areas (ECAs) and operated close to coastal areas which were more affected by the harmful emissions. The operational profile of the reference ship was given in Table 1 and details of individual components, including make, type, characteristics, speed, power, mass and lifespan (whichever relevant) incorporated into the retrofit power plant were summarised in Table 2.

2.2. Operation profiles

The operational profile of the reference ship from 1 January to 31 March 2011 was provided by the ship owner. Two diesel engines were run continuously at constant speed for propulsion purpose while exhaust from the engines was supplied to economisers to produce steam for auxiliary use such as preconditioning heavy fuel oil (HFO) for use in the propulsion engines.

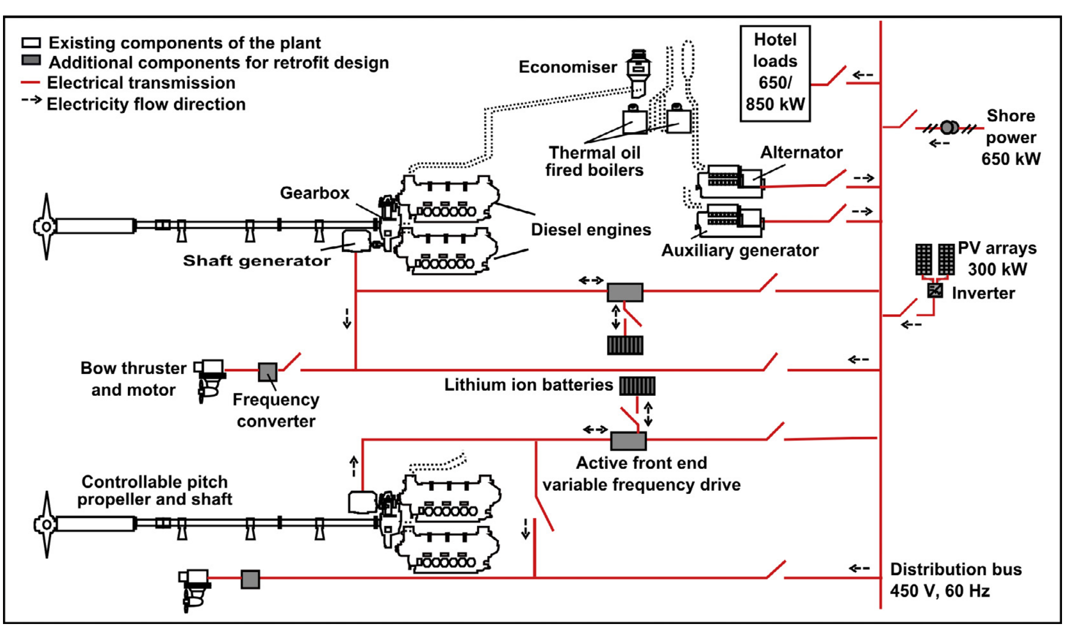

Fig. 1. The theoretical retrofit plant design.

Table 1
Details of the reference ship.

Vessel type	• Roll-on/Roll-off cargo ship
Flag	• Denmark
Year of build	• 2004
Gross and net tonnage	• 21,171 tonnes and 6351 tonnes respectively
Deadweight	• 12,350 tonnes
Light ship	• 10,048 tonnes
Length and breadth	• 183 m × 26 m
Draught	• 6.5 m
Existing power plant	• Main power for propulsion – 4 diesel engines and 2 shaft generators connecting 2 gearboxes respectively driving 2 propellers, in addition to 2 bow thrusters run by built-in motors for manoeuvring purpose • Auxiliary power for hotel service – 2 auxiliary engines functioning as generators, 2 thermal oil boilers and 2 economisers
Sailing profile	• Constantly operated by 12 crews • Travelling daily between Harwich, UK and Europort, Netherlands involving 98.5 and 97.5 nautical miles of transit at sea for 5.46–6.57 h at a speed between 15 and 17 knots respectively • Total journey per voyage is 113.9 and 112.1 nautical miles each • Total time spent in a year for entering, mooring, waiting and leaving the ports: 128.59, 128.29, 2579.95 and 99.96 h respectively in Harwick; 161.42, 161.42, 1702.32 and 149.36 h in Europort
Auxiliary power	• 850 kW at sea and 650 kW in port
Fuel types	• Prior to the enforcement of SOx control in North Sea in November 2007, main engines and auxiliary generators burned (i) marine diesel oil (MDO) before entering or after leaving a port for approximately 0.5–1 h and during manoeuvring and docking; (ii) heavy fuel oil (HFO, with 1% sulphur) when transiting at sea • After the enforcement, both engines and generators burned MDO only • Boilers burned MDO throughout the life cycle
NO_x abatement technique	• Water injection
Lifespan	• Existing plant: 10 years in operation • Retrofit plant: 20 years in operation

Table 2
Details of individual components integrated into the existing and retrofit power plant.

Component, number[a]	Details
Diesel engines, 4 units	Sulzer 8ZA40S, 4-stroke, in-line, medium speed, 510 rpm, non-reversible, 5760 kW, 78,000 kg, 30 years each
Auxiliary generators, 2 units	MAN B&W 7L28/32H, 4-stroke, in-line, 750 rpm, 1563 kW, 39,400 kg, 30 years each
Shaft generators, 2 units	AvK DSG 88M1-4, 2125 kVA, 2125 kg, 30 years each
Gearboxes, 2 units	Renk AD NDSHL3000, output speed of 130 rpm at a reduction ratio of 3.923:1, 510 rpm, 5760 kW, 1415 kg, 30 years each
Propellers and shafts, 2 units	Lips 4CPS160, 4-blade, controllable pitch for ice application with outward turning, diameter of 5 m with 105.4 m shaft, 24,000 kg and 35,400 kg respectively, 30 years each
Bow thrusters and built-in motors, 2 units	Lips CT175H, transverse, of controllable pitch standard design with propeller diameter of 1.75 m, 1465–1755 rpm (input), 316–379 rpm (output), 50–60 Hz, 1000 kW h, 5900 kg, 30 years each
Thermal oil boilers, 2 (plus 2) units	Wiesloch 25V0-13, thermal oil as working fluid, burn MDO with an inlet/outlet temperature of 160/200 °C, 1453 kW, 3170 kg (estimated), 20 years each
Economisers, 2 (plus 2) units	Heatmaster THE 3-60, exhaust gas inlet and outlet temperatures are 206–223 °C and 340–350 °C when engines run at 75–100% maximum continuous rating, 2200 kg (estimated), 15 years each
Frequency converters, 2 (plus 2) units	ABB ACS800-07, standard cabinet-built drive, 500 V, 1000 kW, 1410 kg, 10 years each
Active front end (AFE) Variable Frequency Drives (VFD), 2 (plus 2) units	Ingeteam™ LV4F-32-131WA-348+Z, water cooled cabinet, 480 V, 1774 kVA, 3600 kg, 10 years each
Photovoltaic (PV) system, 1 single-array	1212 units of Kyocera KD245GX-LPB module, 1994 m^2, 25,452 kg, 20 years; and a Schneider Electric GT 250–480 inverter, 300–480 V, 250 kW AC, 2018 kg, 10 years
Lithium-ion battery systems, 2 units	Seanergy® $LiFePO_4$ VL 41M Fe 265 W h/l, rechargeable, 2 MW h, 21,900 kg with cabinets (or 16,800 kg without cabinets), 20 years each
Cold ironing (on-board transformer only)	An ABB RESIBLOC® cast-resin dry transformer, 1000 kVA, 3150 kg, 20 years

[a] The additional number of components used for replacement was shown in brackets. Details for all components, with the exception of PV systems, were presented as individual components.

All propulsion diesel engines were shut down when the ship was waiting in the ports. Bow thrusters were in use or running in standby mode during manoeuvring and mooring. In all cases, an auxiliary generator and a boiler were run to meet auxiliary electrical power and steam services demand. The retrofit power plant was proposed to be installed after the existing ship power plant was operated for 10 years.

For the retrofit system, energy management was modelled using Simplex method developed in General Energy Software (GES) and optimised using Particle Swarm Optimisation (PSO) method developed in Matlab based on voyage conditions. As this article focuses on the environmental implications instead of energy management optimisation, only the operational profiles as developed in these models were elaborated here. When the ship with retrofit power system travelled at sea, main power would be delivered by running 2–4 diesel engines and augmented with energy from a PV and lithium-ion battery systems. Auxiliary load would be (i) partially supplied by shaft generators in PTO mode when connected to diesel engines; or (ii) fully supplied by auxiliary generators while shaft generators work in PTI mode to drive propellers. Thus, at least one of the auxiliary generators would be run when the retrofit ship was transiting at sea. During slow steaming, only one propeller would be powered by PTO/PTI. While manoeuvring, mooring and waiting in port, both diesel engines and auxiliary generators would not be running. Thrusters would be governed by frequency converters to operate at variable speeds during manoeuvring and mooring. In port, cold ironing electricity supply would be used to charge the battery system and supply auxiliary power together with one of the boilers for hotel services.

2.3. Methodology and data sources

In terms of resource consumption and environmental impact, the implications of the marine power plant operation, maintenance and energy management were assessed based on an integrated system approach. LCA was applied for the study, covering the existing plant for 10 years and the retrofit design for 20 years in service. The 20-year lifespan was set for the retrofit plant in line with the total lifespan assumed for a marine vessel i.e. 30 years. This was within the lifespan range of marine vessels presented in literature i.e. 25 years by Schøyen and Sow as well as Carlton et al. [34,63], 30 years by Brosnan [66] and 40 years by Schmidt and Watson [49]. Background data for energy, raw materials and manufacturing processes of individual components were gathered and standardised from various sources e.g. manufacturers, Ecoinvent database (version 2.2) and other literature. The outcome of the Simplex and PSO models under optimum power plant operation detailed usage profile, fuel consumption and power generation of individual components (whichever relevant) on a daily basis. Emissions were estimated based on factors proposed by Cooper [67]. End of life treatment for scrap and used lubricating oil was developed in line with the Ecoinvent datasets and literature, as summarised in the Supplementary material (Appendix 1). LCA models were created using GaBi (version 6) for individual components. Based on a bottom-up approach, total resource consumption and environmental burdens of the power plant throughout the life cycle were estimated. Components and processes with significant environmental impact were identified and further assessed using sensitivity analysis where alternative scenarios were investigated.

3. Theory

3.1. Emerging technologies

3.1.1. Photovoltaic (PV) systems

Solar cells, modules and panels are the main components of a photovoltaic (PV) system and they differ in terms of size and arrangement. A basic solar cell unit comprises positive and negative semiconductor layers i.e. a PN junction [68]. Two common solar cells are crystalline cells and thin films which are made from silicon (Si) and amorphous silicon (a-Si) respectively. The solar cell absorbs photons from sunlight which releases electrons in the negative layer. These electrons are naturally attracted to the positive layer and their movement across an external circuit creates a voltage differential, resulting in an electric current. Modules, in the form of serial solar cells, can be arranged in series and/or parallel to build up a solar panel. A number of solar panel arrangements have been designed for existing PV systems [69], as follows:

- o strings of parallel panels connected to a converter,
- o only one string of parallel panels to one converter,
- o strings of parallel panels, each with an individual converter connected to a common converter,
- o only one single panel to one converter for a module-integrated converter (MIC) system.

3.1.2. Lithium-ion batteries

The basic structure of batteries comprises one or more electrochemical cells in which each cell consists of a negative electrode (i.e. anode), a positive electrode (i.e. cathode) together with a solid, molten or liquid electrolyte [70]. The electrolyte of lithium-ion batteries is commonly a mixture of 2–4 lithium-based salt solutions which are electronically not conductive but capable of transporting lithium ions [71]. The electrolyte is placed in a polymer or absorbed by a thin fleece to keep the distance travelled by the ions as short as possible and accordingly enhance the power density of the battery. Inside the battery, small particles are covered by a surface film known as a solid-electrolyte-interphase (SEI) [71]. A binder is used to attach the SEI to a current collector for each electrode: lithium–metal-oxide particles (with increased conductivity using graphite) to aluminium foil for the positive electrode and lithium–graphite particles to copper foil for the negative electrode [71]. During discharge, lithium ions travel from lithium–graphite particles on the negative electrode, through the electrolyte, and join lithium–metal-oxide particles next to the positive electrode while electrons also move from the negative to positive electrodes via an external circuit. To avoid permanent damage to a lithium-ion battery, the charging process generally starts when the battery is nearly 80% discharged where lithium ions take a reverse path [70].

3.1.3. Power take-off/power take-in (PTO/PTI) systems

Traditionally, a shaft generator functions as an alternator to produce ship electrical power when the armature conductors of the shaft generator are cut by the magnetic field produced due to the rotation of the propeller shaft or main engine [72]. As the shaft generator is mechanically driven by a main engine directly or via a reduction gearbox to drive the propeller, it is also known as a power take-off (PTO) system. The voltage and frequency of PTO systems vary with changing engine speed following the sailing profile of the vessel. As power distributed by the main switch board is of constant voltage and frequency, the presence of a frequency control system (e.g. bi-directional converters) is essential to maintain the voltage and frequency of the PTO system at any engine speed. If electrical power is supplied to the shaft generator from the vessel's auxiliary power, the shaft generator will now motor and act as a power take-in (PTI) system. This is often used to assist ship propulsion and drive the propeller at a reduced speed [72]. During an emergency when the main engines fail, the PTI system can be powered by auxiliary generators to drive the propulsion system to provide a take-me-home function.

3.1.4. Electrical components

Electrical components such as direct frequency converters and variable frequency drives are necessary to ensure the efficiency of thrusters and shaft generators. Direct frequency converters e.g. matrix converters constructed from gate turn-off thyristors or transistors are AC–AC converters which change voltage and frequency of AC inputs directly [73]. VFDs, also known as voltage source inverters (VSIs), are frequency converter drives comprised of insulated-gate bipolar transistor (IGBT) and diodes [74]. VFDs are used to change voltage sources into outputs with waveforms resembling a sine wave.

3.1.5. Cold ironing

Cold ironing is also referred to as shore-side power [75], shore connection or on-shore power supply [76]. Traditionally, when a ship berths, its auxiliary engine(s) and boilers stay in operation to provide hotel services. In contrast, cold ironing allows hotel loads to be met without disruption while the auxiliary engines are stopped by connecting the ship into a local power supply [76]. The electrical infrastructure development at ports and on-board ships involves not only large financial investment but also substantial technical barriers. In addition to the diversity of voltage, frequency and power requirements and inconsistency of connectors and cables used on-board different ship types, the high cost of on-shore electricity in some regions also hinders the uptake of this technology [76]. Recent studies Hall and Gibbs et al. [75,77] also concluded that the benefit of cold ironing is greatly dependent upon the way on-shore electricity is generated: only if renewable energy sources e.g. hydroelectric, nuclear, solar, etc. is primarily employed, will the cold ironing be promising and advantageous in emission reduction. Therefore, countries which rely more on fossil fuels for power generation will stand less chance to take any advantage.

3.2. LCA in accordance with ISO Standards

The principles and framework of LCA have been documented in ISO14040 [78] by the International Organisation for Standardisation (ISO) along with relevant requirements and guidelines [79]. Goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation are the four iterative phases of an LCA study, as shown Fig. 2.

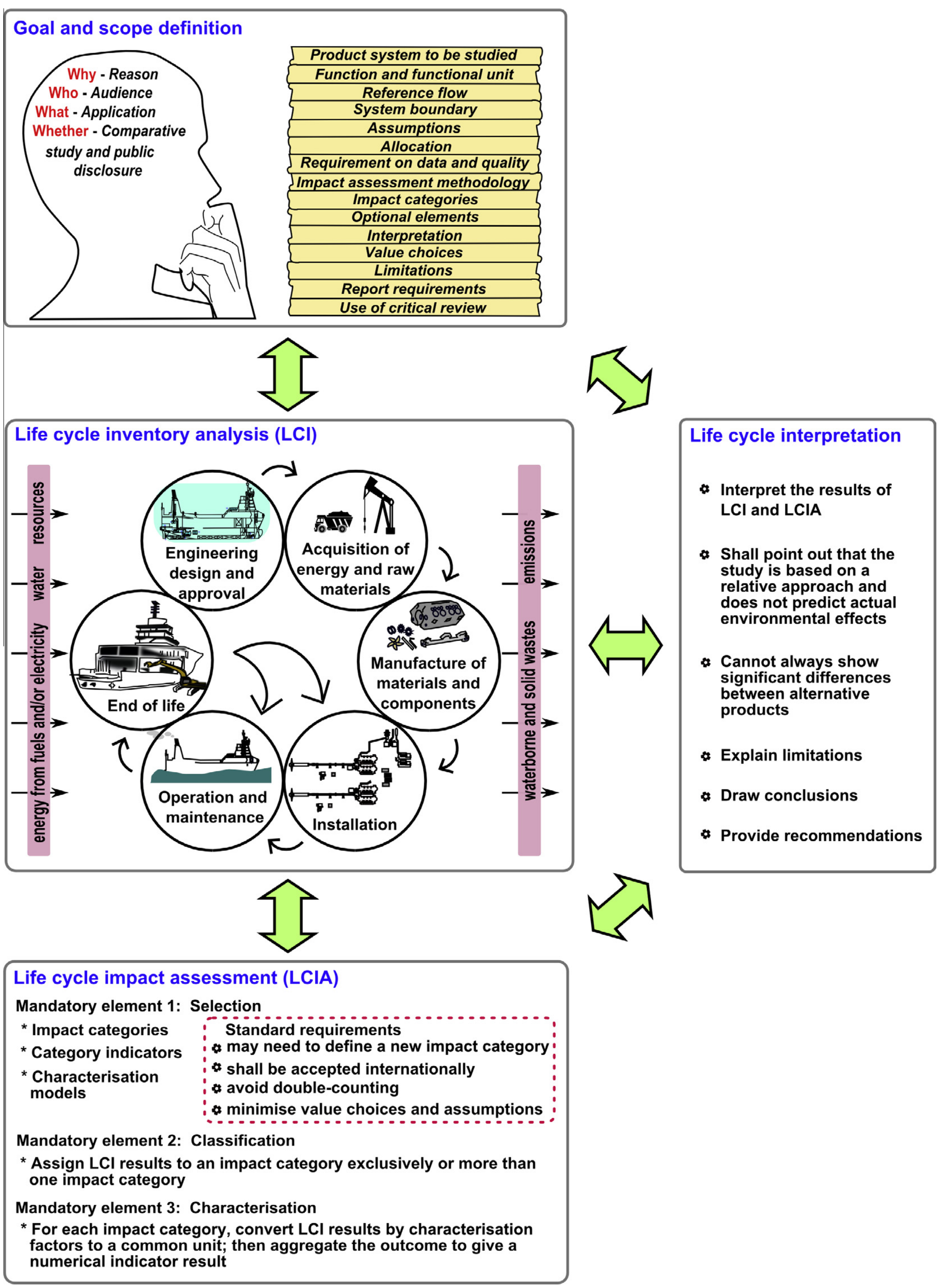

Fig. 2. LCA framework applied in this study as adopted from ISO14040.

The goal of an LCA study can be defined by answering why, who, what and whether or not, i.e. why the study is carried out; who the audience is; what application(s) is for; and whether the results are to be presented in a comparative study and/or disclosed to the public. The scope definition constructs a provisional plan of the study i.e. identifying product system to be studied and its function(s); defining functional unit (and reference flow, if applicable), setting up the system boundary; uncovering any assumptions, value choices and limitations; outlining how to deal with allocation; specifying requirements on data, data quality and the report; selecting LCIA methodology and impact categories; indicating if optional elements and a critical review are to be included; and telling how results are to be interpreted.

An LCA study may consider any life cycle phases of the product system i.e. engineering design and approval, natural resource acquisition for energy and raw materials, manufacturing, installation, operation, maintenance, and end of life management. To accomplish the LCI for the study, inputs and outputs involved in the life cycle phases under study are compiled from a range of academic, trade and government publications or based on theoretical calculation, simulation, laboratory testing, database, expert judgement, etc. The LCI results are then used for LCIA and life cycle interpretation in the successive steps.

Selecting relevant characterisation model(s), impact categories and indicators, classifying LCI results to impact categories, and characterising LCI results based on established factors to result in LCIA results (also referred to as indicator results) are the three mandatory procedures of LCIA. Consistency with the goal and scope definition, any of the three optional procedures, namely normalisation, grouping and weighting, can be performed, in which the LCIA results are compared to a reference, organised systematically based on the set value, or converted to a single score using weighting factors respectively. In accomplishing the tasks, some LCA researchers develop characterisation models for the study; others take advantage of existing LCA software.

Life cycle interpretation involves the identification of significant issues and evaluation of LCI and LCIA results in terms of consistency, completeness and sensitivity. Sensitivity of the results is subject to uncertainty and methodological choice; both issues can be dealt with using scenario analysis. Alternatively, uncertainty can be addressed with additional data collection from further research or other approaches for uncertainty analysis e.g. uncertainty factors, Monte Carlo, Bayesian, etc. Methodological choice can be handled via sensitivity analysis, e.g. advanced statistics. At this stage, it is essential to recognise that the results only provide an estimate on the environmental burdens where absolute accuracy is impossible in any case. Therefore, explaining limitations, making recommendations and drawing conclusions shall be presented.

4. Results and discussion

4.1. Goal and scope definition

The reason for conducting this LCA study was to explore the environmental implications of redesigning the marine power plant on-board a RoRo cargo ship. Marine stakeholders including ship owners, industry practitioners, researchers, academics and the public were targeted audience for this study. The results were made accessible to the public through this article and could be used for a comparative study in future work. The product system under study was the power plant on-board a reference ship, covering existing and retrofit configurations for 10 and 20 years in operation respectively. The function was to supply main and auxiliary power while the functional unit was the operation of the power plant over 30 years (i.e. existing and retrofit plants for 10 and 20 years respectively) on-board a RoRo cargo ship on regular routes. The environmental impacts of the power plant were assessed based on an integrated system approach where all technologies, as summarised in Table 2, were included as a part of the system boundary. As the product system involved components of different lifespans, allocation was avoided in the study via system expansion in which replacing components were included. Life cycles under study covered the acquisition of energy and raw materials, manufacturing, operation and maintenance, dismantling and the end of life management. It was assumed that (i) the lifespan for a marine power plant was 30 years; (ii) the environmental impacts during engineering design and installation were insignificant, as did auxiliary equipment such as fuel oil systems, piping, cables and switchboards; (iii) neither materials nor devices were lost or defective during manufacturing and operation; (iv) chemicals required for manufacturing and end of life treatment were reused; and (v) at the end of life, parts and metallic scrap from engines and generators were reused (30%), recycled (30%) or disposed to incineration plants and landfill sites (20% each); for other components, 33.3% of the parts and metallic scrap were recycled, disposed to incineration plants or landfilled respectively. In relation to data requirements, average data gathered from existing database and literature were used for most life cycle phases but specific data i.e. simulation results based on real-time operational profiles were required for the operation phase. The environmental impacts were assessed using both midpoint and endpoint approaches i.e. CML2001, Eco-indicator99 and ILCD recommended methodologies (hereafter 'ILCD') and, accordingly, LCIA results were characterised into a range of impact categories. As no threshold has been defined for the harmfulness of individual impact categories, those with 3 or greater orders of magnitude were recognised as significant in this study. LCIA results were presented without normalisation, weighting and grouping to enable comparative study and validation in future work. In interpreting LCIA results, sensitivity and uncertainty of the results were investigated using scenario analysis. For individual technologies and components, multiple choices for manufacturers, models and manufacturing plants have been available worldwide. Due to time and resource constraints, the locations of manufacture and recycling sites were not taken into account, and therefore, transportation was excluded. Onshore infrastructure and transformers are required for cold-ironing implementation; however only transformer on-board the ship was included within the system boundary.

4.2. LCI – resources and emissions

Among a wide variety of materials required for manufacturing components that were incorporated into the power plant under study, aluminium, copper, steel and cast iron, in ascending order ranging between 2.9×10^4 kg and 2.9×10^5 kg, were most commonly consumed, as illustrated in Fig. 3(a). The LCI showed that diesel engines, propellers and shafts, and variable frequency drives played a significant role in consuming these four materials – diesel engines were accountable for 29.3% of aluminium, 35.2% of steel and 76.2% of cast iron consumption; propellers and shafts used 73.4% of copper and 38.8% of steel; and variable frequency drives were responsible for 25.3% of aluminium consumption. In total, the manufacturing processes involved 2.7×10^4 MJ and 2.4×10^5 MJ of energy due to industrial furnaces burning heavy and light fuel oils respectively, together with 3.3×10^5 MJ of energy from electricity and 6.2×10^5 MJ of heat from gas boilers. The manufacturing processes of diesel engines, propellers and shafts, diesel generators, frequency converters and the PV system were the significant sources of total energy consumption. Among

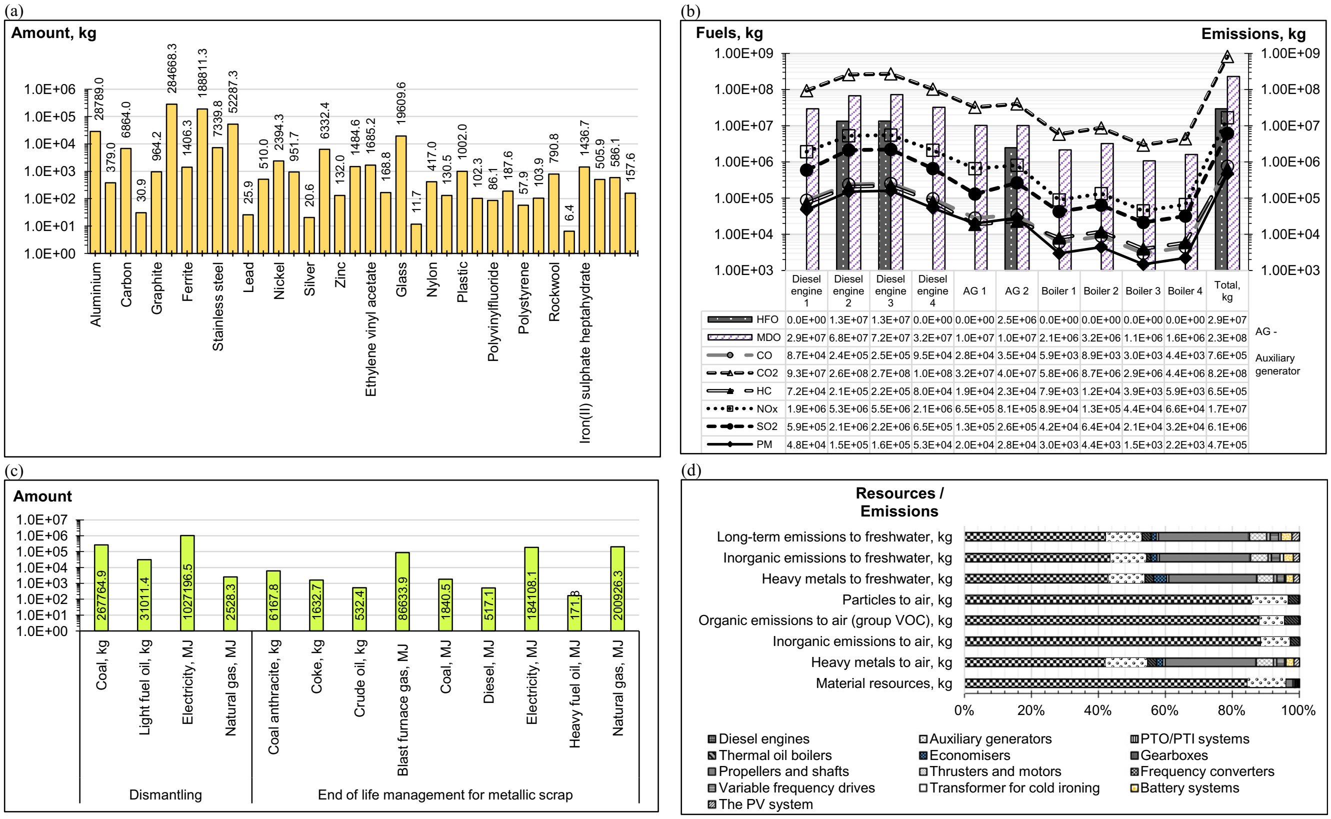

Fig. 3. Resources and/or emissions (a) materials used in manufacturing components, in kg; (b) fuel consumption and emissions released during the operation of marine power plant, as per components, over 30 years; (c) resource and energy consumption during dismantling and end of life phases; and (d) emissions of the power plant from acquisition of raw materials and energy to end of life management as per individual technologies, which were estimated via LCA models developed in GaBi for base case scenario.

all, diesel engines required 53.4%, 46.5% and 48.0% of energy supplied from burning heavy and light fuel oils by furnaces and natural gas by boilers respectively, followed by propellers and shafts i.e. 20.3%, 17.7% and 18.3% respectively, in addition to 13.5%, 11.7% and 12.1% respectively used in manufacturing diesel generators. Frequency converters and PV systems were the two biggest consumers of electricity, i.e. 37.6% and 19.2% respectively. Besides, glass and iron sulphate (II), heptahydrate appeared as the largest constituent of non-metallic materials and chemicals being consumed, i.e. 2.0×10^4 kg and 1.4×10^3 kg, which were almost entirely consumed for the manufacture of PV and battery systems respectively.

Based on the optimised profile for the vessel, the operation of the marine power plant consumed 2.9×10^7 kg of HFO and 2.3×10^8 kg of MDO, which were burned by diesel engines, auxiliary generators and boilers, and consequently, released 8.2×10^8 kg of CO_2, 1.7×10^7 kg of NO_x, 6.1×10^6 kg of SO_2, 7.6×10^5 kg of CO, 6.5×10^5 kg of hydrocarbon (HC) and 4.7×10^5 kg of PM, as illustrated in Fig. 3(b). The analysis showed that diesel engines were accountable for 91.6% of total HFO consumption, 87.7% of total MDO consumption and more than 87% of total emissions released. It was mainly because of the running of between 2 and 4 diesel engines for ship propulsion and auxiliary power supply when the reference ship was transiting at sea. Additional resources were consumed during ship maintenance. Based on information provided by industrial partners, replacing lubricating oil on a regular basis amounted to 5.1×10^4 kg, was necessary for optimal performance of the power plant. To treat and recover used lubricating oil, 120–170 kg of diesel, light fuel oil and liquefied petroleum were required respectively, in addition to energy supplied from electricity and natural gas, i.e. 3.2×10^6 MJ and 2.8×10^5 kg respectively. Similarly, resources and energy were consumed in dismantling the power plant and handling metallic scrap at the end of life, as illustrated in Fig. 3(c). The LCI showed that coal was the most widely consumed resource i.e. 2.7×10^5 kg while electricity was the most popular source of energy i.e. 1.2×10^6 MJ during dismantling and end of life phases. Resources and energy consumed in non-metallic scrap treatment were negligible and therefore not elaborated here.

Throughout the full life cycle, emissions were released into various ecosystems such as air, freshwater, sea water, agricultural soil and industrial soil, as indicated by the outcome of LCA models developed using GaBi. Emissions to freshwater and air were worth noting, including 6.9×10^2 kg of heavy metals and 2.7×10^5 kg of inorganic emissions to freshwater, 1.1×10^4 kg of heavy metals, 4.8×10^5 kg of particles, 6.7×10^5 kg of organic emissions and 8.4×10^8 kg of inorganic emissions to air. By taking the whole system and all life cycle phases into account, it was found that diesel engines remained the main source of emissions (as well as material resources). Their contribution to the total amount of particles, organic and inorganic emissions to air was profound, as shown in Fig. 3(d). For each category, the release of PM, HC and CO_2 into the atmosphere during the operation phase appeared to be the major source. CO, NO_x and SO_2 were other sources of inorganic emissions; however, they were less noticeable as their orders of magnitude were 2–3 times less than that of CO_2. In addition, diesel engines also resulted in 42.2–43.5% of heavy metal emissions to air (i.e. iron) and long-term, inorganic as well as heavy metal emissions to freshwater (i.e. aluminium, copper and iron respectively), as the consequences of disposing metallic scrap to incineration plants and landfill sites. Emissions attributable to propellers and shafts were mainly from metallic scrap disposal, with similar wastes but accounting for approximately 27% of the total amount of these four emission categories, individually. In this context, emissions attributable to auxiliary generators were more consistent across all categories, ranging from 7.4% to 12.5%, with evident wastes from both operation and metallic scrap disposal. Emissions to sea water, agricultural and industrial soils ranged 1–3 orders of magnitude, as indicated by the outcome of the models in GaBi. Such magnitude was perceived as relatively negligible when compared with emissions to freshwater and air, which were greater than 5 orders of magnitude with the exception of heavy metals. The trend of less emissions to agricultural and industrial soils and more emissions to freshwater and air was justifiable, considering the length of time involved during manufacturing and operation phases i.e. a few months versus 30 years. During operation phase, emissions released from the power plant were primarily to the air instead of sea water, which consequently showed less significant emissions to sea water.

4.3. LCIA results

Covering raw materials and energy acquisition, manufacturing, operating, maintaining, dismantling and end-of-life management, the life cycle implications of the power plant for the environment and human beings were characterised into individual impact categories. Using CML2001, Eco-Indicator99 and ILCD, the LCIA results for most impact categories were greater than 5 orders of magnitude, as shown in Fig. 4 (in which individual impacts were labelled as I–XXVI on the right and the bottom axes while the magnitude was scaled on the left axis). Based on a midpoint approach, Aquatic Ecotoxicity was identified by both CML2001 and ILCD as the most significant environmental burdens attributable to the power plant, i.e. 3.4×10^{10} and 1.6×10^{8} kg DCB equivalent of Marine and Freshwater Aquatic Ecotoxicity Potential respectively by CML and 7.7×10^{9} CTUe of Ecotoxicity for Aquatic Freshwater by ILCD. This was in proximity to LCIA results estimated for Ecosystem Quality – Ecotoxicity based on an endpoint approach i.e. 2.2×10^{7} PDF m^2 a, which was the second highest impact assessed by Eco-Indicator99. The most burdensome impact category reported by Eco-Indicator99 was Ecosystem Quality – Acidification, which accounted for 1.0×10^{8} PDF m^2 a. The result was more significant than the relevant assessments made by the other two methodologies by one order of magnitude. The use of distinct environmental mechanisms and indicators in developing these methodologies was perceived as a plausible explanation for the difference in the results. In relation to the other impacts assessed by both CML2001 and ILCD i.e. Global Warming Potential, the estimates were in agreement with the result of applying the same method developed by Intergovernmental Panel on Climate Change (IPCC).

The environmental burdens of the power plant could be further analysed to identify the significant causes of individual impacts. By analysing the contribution of individual technologies towards the overall environmental burdens of the power plant (in percentage, presented on the top axis of Fig. 4), the environmental burdens caused by diesel engines, auxiliary generators, propellers and shafts, as well as other components, were disproportionate to their mass, i.e. 48.4%, 18.4%, 12.2% and 21% of the total mass of the power plant. For all categories, diesel engines played a pronounced role in instigating 42.9–92.4% of the environmental burdens. When compared to other technologies (with the exception of diesel engines), the contribution of auxiliary generators was observable for most impact categories ranging 7.7–13.4% with the exception of Terrestric Ecotoxicity Potential (34.9%) and Abiotic Depletion Potential of Fossil (16.8%) assessed by CML2001; Resources – Fossil Fuels (16.8%), Resources – Minerals (3.2%) and Ecosystem Quality – Land-use (1.8%) assessed by Eco-Indicator99; and Resource Depletion, Fossil and Mineral (21.8%) assessed by ILCD. This was followed by propellers and shafts which brought approximately 28% of Marine and Freshwater Aquatic Ecotoxicity Potential (by CML2001), Ecosystem Quality – Ecotoxicity (by Eco-Indicator99) and Ecotoxicity for Aquatic Freshwater (by ILCD). The following key contributors were identified for individual impacts:

- Consuming resources: (i) cast iron: Human Toxicity Potential by CML2001; (ii) chromium for stainless steel production: Terrestric Ecotoxicity Potential by CML2001; (iii) tin and copper: Resources – Minerals by Eco-Indicator99 and Resource Depletion, Fossil and Mineral by ILCD; (iv) crude oil: Abiotic Depletion (ADP fossil) by CML2001; (v) resources – Fossil Fuels by Eco-Indicator99; and (vi) water: Total Freshwater Consumption by ILCD.
- Storing resources: Ecosystem Quality – Land-use.
- Operating diesel engines and auxiliary generators: Global Warming Potential (including and excluding biogenic carbon), Human Toxicity Potential; Photochemical Ozone Creation Potential, Acidification Potential and Eutrophication Potential by CML2001; Ecosystem Quality – Acidification and Human Health – Respiratory (Inorganic) by Eco-Indicator99; and Global Warming Potential (including and excluding biogenic carbon), Terrestrial Eutrophication, Photochemical Ozone Formation, Acidification, PM/Respiratory Inorganics and Marine Eutrophication by ILCD.
- Disposing metallic waste of diesel engines, auxiliary generators, propellers and shafts to incineration plants: Marine and Freshwater Aquatic Ecotoxicity Potential by CML2001; Ecosystem Quality – Ecotoxicity by Eco-Indicator99; and Ecotoxicity for Aquatic Freshwater by ILCD.

From a life cycle perspective, the analysis showed that despite a large amount of resources including energy and materials were involved during acquisition and manufacturing phases, most environmental burdens of the power plant occurred during operation and end of life phases. A correlation between key contributors and significance of the impacts was observed: while resource consumption and storage led to impacts which were less significant, operating diesel engines and auxiliary generators resulted in impacts which were more significant; however, disposing metallic waste was the main cause for the most significant impact categories assessed by CML2001, Eco-Indicator99 and ILCD. It was worth noting that the LCI and LCIA results presented here were subject to assumptions and limitations (see Section 4.1). Varying any assumptions and overcoming any limitations were likely to increase the magnitude of LCI results (unless a shorter lifespan was defined or less scrap was handled) and exert an influence on the LCIA results. Considering the complex nature of marine power plants and the massive scope of the studies, the influence of these assumptions and limitations could be pronounced, moderate or minimal. However, no conclusive correlation could be suggested without in-depth investigation. Among all, only the end of life scenario was studied as a part of life cycle interpretation in Section 4.4 whilst others were not further addressed due to resource constraints. The influence of individual assumptions and limitations, should be examined one by one in future study.

4.4. Life cycle interpretation

To fully understand the environmental implications of the power plant under study, a number of additional scenarios were explored in line with issues that have been of special interest to

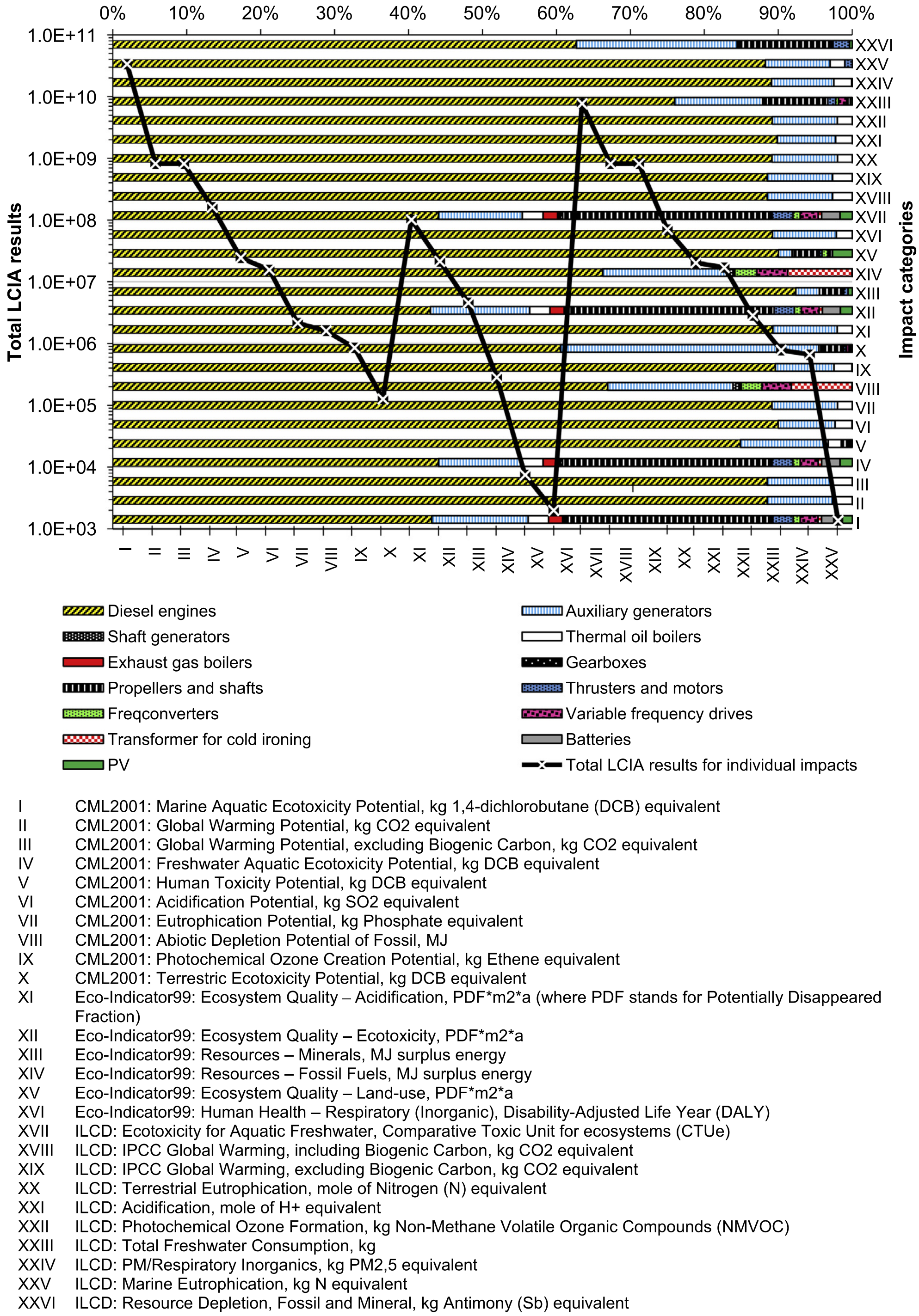

Fig. 4. Total environmental burdens attributable to the power plant, characterised as per impact categories contributed by individual components from energy and material acquisition to the end of life. To find the magnitude of a particular impact category, look at the bottom and the left axes; to find contributions of components towards a particular impact category, look at the right and the top axes.

marine stakeholders and LCA community from a life cycle perspective. Results gained from these scenarios were compared with the base case scenario i.e. LCI and LCIA results presented in earlier sections.

The LCIA results, as illustrated in Fig. 4, showed that new components that were incorporated into the retrofit power plant were accountable for less than 8.0% of individual impacts, with the exception of Abiotic Depletion of Fossil (15.0%, assessed by CML2001) and Resources – Fossil Fuels (15.9%, assessed by Eco-Indicator99). Without further analysis, it was uncertain whether these new components had no significant environmental impacts at all or they reduced the environmental burdens of the power plant substantially. The uncertainty was addressed by examining the significance of the retrofit design (as implemented in the base case) based on a 'business as usual' scenario, an integrated system approach applied which was consistent with the defined goal and scope of the study.

In the 'business as usual' scenario, the conventional plant was operated for 30 years where no retrofit design was implemented. The LCI showed that prior to the operational phase, 5.2×10^3 kg of copper, 1.4×10^4 kg of aluminium, 1.2×10^5 kg of steel, most non-metallic and chemicals, to name but a few, would not be consumed. Consequently, energy demand supplied by operating furnaces, boilers and electricity during manufacturing processes could be reduced by 1.5×10^4 MJ, 4.7×10^4 MJ and 1.9×10^5 MJ respectively. Having stated this, an additional 2.1×10^7 kg of MDO would be consumed during the vessel operation phase if the power plant continued operation without implementing retrofit changes to the plant, which was estimated to release more emissions, i.e. 3.2×10^4 kg of PM, 5.5×10^4 kg of CO, 6.6×10^4 kg of HC, 5.5×10^5 kg of SO_2, 9.6×10^5 kg of NO_x and 5.5×10^7 kg of CO_2. As 6.3×10^3 kg less lubricating oil was needed for maintaining components, energy required for treating and recovering used lubricating oil could be scaled down by 9.1×10^4 MJ. From a full life cycle perspective, the LCI showed that the 'business as usual' scenario would result in less heavy metals to air, inorganic and long-term emissions to freshwater by 1.1×10^3 kg, 3.1×10^4 kg and 2.2×10^4 kg respectively at the expense of releasing more inorganic, organic and particle emissions to air and heavy metals to freshwater by 5.6×10^7 kg, 5.9×10^4 kg, 3.1×10^4 kg and 2.7×10^3 kg respectively. As illustrated in Fig. 5(a), the LCIA results showed that some environmental impacts, in particular those relevant to ecotoxicity and resource depletion, were less burdensome in the 'business as usual' scenario. However, other impacts covering global warming, human toxicity, acidification, eutrophication, etc. could be reduced by 4–7 orders of magnitude if the retrofit changes to the plant as proposed in the base case were implemented. Ecotoxicity potential presented in the base case was much

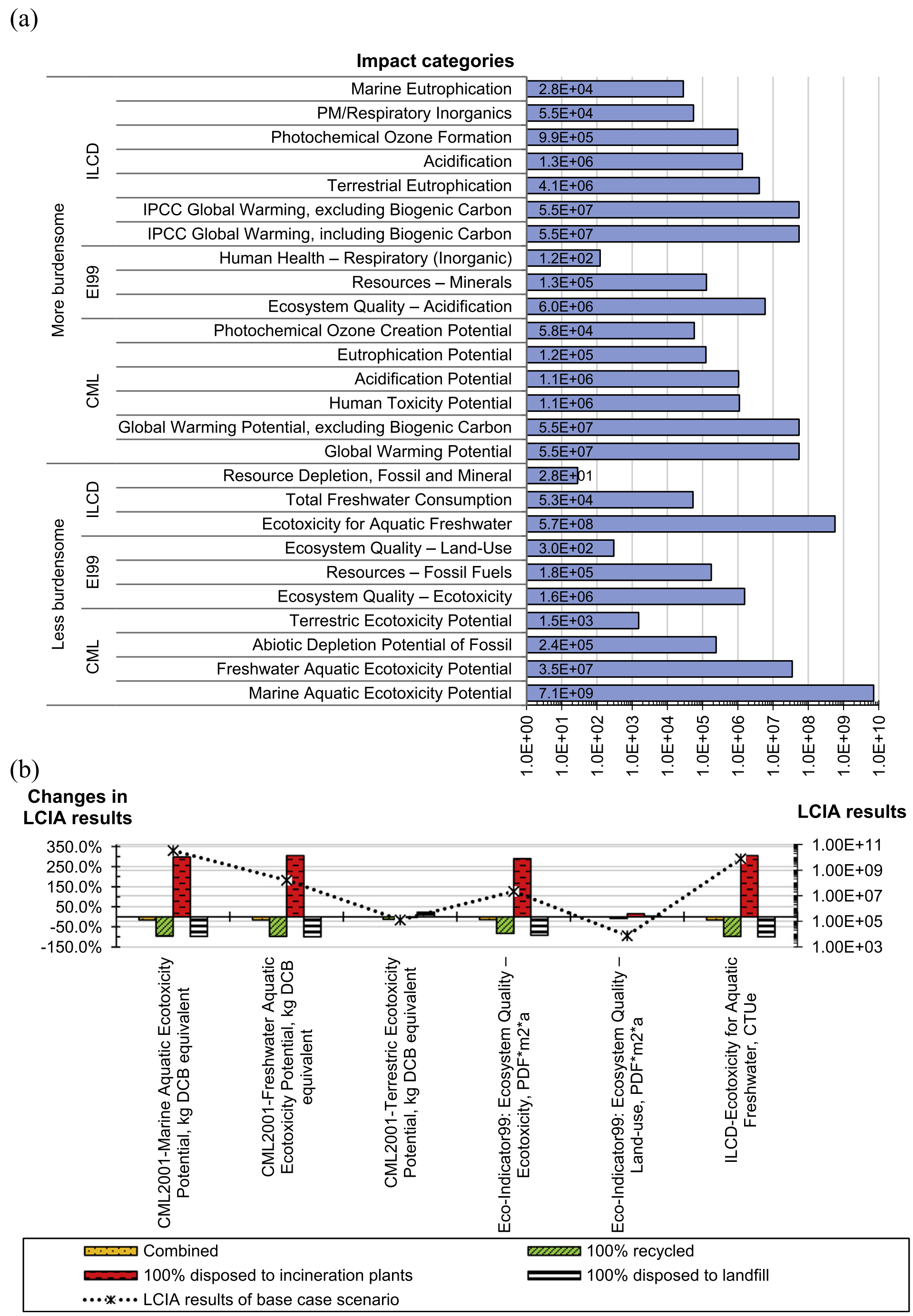

Fig. 5. Difference in LCIA results (a) when the 'business as usual scenario' was compared to the base case, indicating less burdens across impacts that were related to ecotoxicity and resource depletion; and (b) for ecotoxicity potential assessed by CML2001, Eco-Indicator99 and ILCD due to scrap handling scenarios.

higher than that of the 'business as usual' scenario as a result of additional metallic scrap being disposed to incineration plants at the end of life phase.

Disposing metallic scrap to incineration plants were identified as the major cause of ecotoxicity potential, which was reported as one of the two most significant impacts for both base case and 'business as usual' scenarios based on LCIA results shown by CML2001, Eco-Indicator99 and ILCD. For these LCA models, a reusing–recycling–incineration–landfill ratio of 3:3:2:2 was adopted for the metallic scrap of engines and generators while for other components, 33.3% of metallic scrap was recycled, disposed to incineration plants or landfilled respectively. Although full recycling (disposal to incineration or landfill sites) is not practised in reality, a theoretical analysis could enhance understanding in this matter. Sensitivity analysis was extended to cover four scrap handling scenarios at the end of life of the retrofit plant: (i) 100% recycled; (ii) 100% sent to incineration plants; (iii) 100% landfilled; and (iv) 50% recycled, 20% sent to incineration plants and 30% sent to landfill sites (hereafter 'the combined scenario') to shed light on the possibility to alleviate Ecotoxicity Potential. As illustrated in Fig. 5(b), Ecotoxicity Potential assessed by CML2001, Eco-Indicator99 and ILCD was sensitive with scrap handling scenarios. The potential was lower when more scrap was recycled or landfilled i.e. declining by 15.3–100.0% if the scrap was fully recycled or landfilled. Nevertheless, the fallout of incineration was very large i.e. increasing up to 305% if scrap was fully sent to incineration plants. In these four scenarios, changes in LCIA results when compared to the base case scenario as shown by CML2001, Eco-Indicator99 and ILCD were in agreement. Among all, global warming potential, acidification, photochemical ozone depletion and resource depletion increased by less than 0.8% while eutrophication, human toxicity and fossil fuel depletion differed by less than 2.7%. Such a variation should be taken into consideration in deciding the end of life scenarios of the power plant as it implies a difference in individual impacts by 1–6 orders of magnitude.

Sensitivity analysis, which was performed using scenario analysis, indicated that retrofitting existing power plant with emerging marine power technologies could effectively reduce numerous environmental impacts, which would inevitably come along with an increase in resource depletion. After all, the new components brought about some environmental impacts but such burdens, altogether, were modest and only accounted for less than 15.8% of the overall amount. The most significant environmental impact attributable to marine power plant, i.e. ecotoxicity potential, could be diminished by recycling/landfilling more scrap instead of disposal to incineration plants.

5. Conclusions

In this study, LCA was applied to estimate the environmental impacts of a power plant on-board a RoRo cargo ship. The study covered energy and materials acquisition, manufacturing, operation (i.e. 10 years for an existing design and 20 years for a retrofit design incorporating selected emerging technologies i.e. PV system, lithium-ion batteries, PTO/PTI and cold ironing supplemented by frequency converters and variable frequency drives), and end of life management. In accordance with ISO Standards on LCA, life cycle phases covered in this study included goal and scope definition, LCI, LCIA and life cycle interpretation, in which resource consumption, emissions and the environmental impacts were estimated. The magnitude of energy and materials involved during acquisition and manufacturing phases was found to be up to 6 orders, each. By characterising the environmental burdens into a range of impacts, such as ecotoxicity, global warming, acidification, eutrophication etc., the study showed that most environmental impacts of the power plant occurred during operation and end of life phases, ranging between 3 and 11 orders of magnitude in which ecotoxicity potential was determined as the most significant impact. Approximately 85% of the total environmental impacts were caused by diesel engines, auxiliary generators, propellers and shafts. The correlation between major sources and impact significance was identified in which resource consumption and storage prior to operation phase, running diesel engines and auxiliary generators during operation, and disposing metallic scrap at the end of life were the main causes of less, moderate and significant impacts, respectively. The environmental benefits of incorporating emerging technologies, although not indicated by LCIA results directly, were verified using sensitivity analysis i.e. scenario analysis in this study. In addition to reducing MDO consumption by 7 orders of magnitude and diminishing global warming, human toxicity, acidification and eutrophication by 4–7 orders of magnitude, the retrofit plant could alleviate its ecotoxicity potential, which was the most significant environmental burden, through recycling or landfilling more scarp at the end of life. While retrofitting marine power plant with emerging technologies added environmental benefits to the reference ship, the full life cycle phases, in particular operation and end of life phases, should be managed appropriately to avoid shifting the burdens from one impact to another. The work presented in this article has bridged existing knowledge gap by applying LCA to scrutinise the environmental impacts of the power plant of a RoRo cargo ship in which retrofit design was considered. The outcome has offered an understanding on significant resource consumption and environmental impacts in addition to the benefits of incorporating emerging technologies into the existing plant, which presents a reference for future work. As a number of factors may have an impact on the environmental burdens of marine power plants, future research shall be extended to cover (i) various vessel types, e.g. general cargo ships, passenger ships, vehicle carriers, tankers, bulkers, etc.; (ii) different operational profiles, e.g. short sea and deep sea shipping; and (iii) various retrofit designs taking advantages of other emerging technologies, e.g. sails, waste heat recovery systems, full electric configuration, etc. The influence of assumptions, made in relation to lifespan, engineering design and installation, auxiliary equipment, material loss, equipment malfunction and end of life treatment for chemicals, shall be examined in future work to identify correlation between these parameters and LCIA results, if there is any. Limitations presented in this work i.e. location of manufacture and recycling sites taking account of transportation shall also be addressed in future work.

Acknowledgements

Research disseminated in this article is the outcomes from a European Commission funded FP7 project 'INOvative Energy MANagement System for Cargo SHIP' (INOMANS^{2}HIP, grant agreement no: 266082) and a research funded by the Research Councils UK Energy Programme entitled 'Sustainable Thermal Energy Management Network' (SusTEM, EPSRC Reference: EP/K039377/1). The authors would like to thank Imtech Marine Netherlands BV, Netherlands Organisation for Applied Scientific Research (TNO), Offshore Renewable Energy Catapult (NAREC), Wärtsilä Netherlands BV and the ship owner for their technical support and knowledge exchange. Data supporting this publication is openly available under an 'Open Data Commons Open Database License'. Additional metadata are available at: 10.17634/123881-1. Please contact Newcastle Research Data Service at rdm@ncl.ac.uk for access instructions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enconman.2016.03.032.

References

[1] Fagerholt K, Psaraftis HN. On two speed optimization problems for ships that sail in and out of emission control areas. Transport Res Part D – Transp Environ 2015;39:56–64.

[2] Golomb D. Transport systems for ocean disposal of CO_2 and their environmental effects. Energy Convers Manage 1997;38(Supplement):S279–86.

[3] Kildow J. Testing the waters: an analytical framework for testing the political feasibility of scenario-based proposals for disposing of CO_2 in the oceans. Energy Convers Manage 1997;38(Supplement):S295–300.

[4] Heitmann N, Peterson S. The potential contribution of the shipping sector to an efficient reduction of global carbon dioxide emissions. Environ Sci Policy 2014;42:56–66.

[5] Westerlund J, Hallquist M, Hallquist ÅM. Characterization of fleet emissions from ships through multi-individual determination of size-resolved particle emissions in a coastal area. Atmos Environ 2015;112:159–66.

[6] Wang C, Corbett JJ, Firestone J. Modeling energy use and emissions from North American shipping: application of the ship traffic, energy, and environment model. Environ Sci Technol 2007;41(9):3226–32.

[7] Moreno-Gutiérrez J et al. Methodologies for estimating shipping emissions and energy consumption: a comparative analysis of current methods. Energy 2015;86:603–16.

[8] Ushakov S et al. Emission characteristics of GTL fuel as an alternative to conventional marine gas oil. Transport Res Part D – Transp Environ 2013;18:31–8.

[9] Winnes H, Fridell E. Emissions of NOX and particles from manoeuvring ships. Transport Res Part D – Transp Environ 2010;15(4):204–11.

[10] Stevens L et al. Is new emission legislation stimulating the implementation of sustainable and energy-efficient maritime technologies? Res Transport Bus Manage 2015.

[11] Lun YHV et al. Environmental governance mechanisms in shipping firms and their environmental performance. Transport Res Part E – Log 2015;78:82–92.

[12] Uriondo Z et al. Effects of charged air temperature and pressure on NOx emissions of marine medium speed engines. Transport Res Part D – Transp Environ 2011;16(4):288–95.

[13] Grados C Vanesa Durán et al. Correcting injection pressure maladjustments to reduce NOX emissions by marine diesel engines. Transport Res Part D – Transp Environ 2009;14(1):61–6.

[14] Duran V, Uriondo Z, Moreno-Gutiérrez J. The impact of marine engine operation and maintenance on emissions. Transport Res Part D – Transp Environ 2012;17(1):54–60.

[15] Di Natale F, Carotenuto C. Particulate matter in marine diesel engines exhausts: emissions and control strategies. Transport Res Part D – Transp Environ 2015;40:166–91.

[16] Nielsen RF, Haglind F, Larsen U. Design and modeling of an advanced marine machinery system including waste heat recovery and removal of sulphur oxides. Energy Convers Manage 2014;85:687–93.

[17] Yang M-H. Thermal and economic analyses of a compact waste heat recovering system for the marine diesel engine using transcritical Rankine cycle. Energy Convers Manage 2015;106:1082–96.

[18] Haglind F. A review on the use of gas and steam turbine combined cycles as prime movers for large ships. Part I: background and design. Energy Convers Manage 2008;49(12):3458–67.

[19] Haglind F. A review on the use of gas and steam turbine combined cycles as prime movers for large ships. Part II: previous work and implications. Energy Convers Manage 2008;49(12):3468–75.

[20] Gómez J Romero et al. Analysis and efficiency enhancement of a boil-off gas reliquefaction system with cascade cycle on board LNG carriers. Energy Convers Manage 2015;94:261–74.

[21] Prevention of air pollution from ships. <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx> [cited 2014 31 December].

[22] Yang ZL et al. Selection of techniques for reducing shipping NOx and SOx emissions. Transport Res Part D – Transp Environ 2012;17(6):478–86.

[23] Ma H et al. Well-to-wake energy and greenhouse gas analysis of SOX abatement options for the marine industry. Transport Res Part D – Transp Environ 2012;17(4):301–8.

[24] Jiang L, Kronbak J, Christensen LP. The costs and benefits of sulphur reduction measures: sulphur scrubbers versus marine gas oil. Transport Res Part D – Transp Environ 2014;28:19–27.

[25] Brynolf S et al. Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. Transport Res Part D – Transp Environ 2014;28:6–18.

[26] Psaraftis HN, Kontovas CA. Speed models for energy-efficient maritime transportation: a taxonomy and survey. Transport Res Part C – Emerg 2013;26:331–51.

[27] Psaraftis HN, Kontovas CA. Balancing the economic and environmental performance of maritime transportation. Transport Res Part D – Transp Environ 2010;15(8):458–62.

[28] Kim H-J et al. An epsilon-optimal algorithm considering greenhouse gas emissions for the management of a ship's bunker fuel. Transport Res Part D – Transp Environ 2012;17(2):97–103.

[29] Fagerholt K et al. Maritime routing and speed optimization with emission control areas. Transport Res Part C – Emerg 2015;52:57–73.

[30] Niknam T et al. A modified shuffle frog leaping algorithm for multi-objective optimal power flow. Energy 2011;36(11):6420–32.

[31] Narimani MR et al. A novel approach to multi-objective optimal power flow by a new hybrid optimization algorithm considering generator constraints and multi-fuel type. Energy 2013;49:119–36.

[32] Niknam T, Azizipanah-Abarghooee R, Narimani MR. An efficient scenario-based stochastic programming framework for multi-objective optimal micro-grid operation. Appl Energy 2012;99:455–70.

[33] Patricksson ØS, Fagerholt K, Rakke JG. The fleet renewal problem with regional emission limitations: case study from Roll-on/Roll-off shipping. Transport Res Part C – Emerg 2015;56:346–58.

[34] Schøyen H, Sow H. A decision making tool concerning retrofit of shaft generator frequency converter. Ocean Eng 2015;109:103–12.

[35] Ölçer A, Ballini F. The development of a decision making framework for evaluating the trade-off solutions of cleaner seaborne transportation. Transport Res Part D – Transp Environ 2015;37:150–70.

[36] Dimopoulos GG et al. A general-purpose process modelling framework for marine energy systems. Energy Convers Manage 2014;86:325–39.

[37] Livanos GA, Theotokatos G, Pagonis D-N. Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. Energy Convers Manage 2014;79:640–51.

[38] Sciberras EA, Zahawi B, Atkinson DJ. Electrical characteristics of cold ironing energy supply for berthed ships. Transport Res Part D – Transp Environ 2015;39:31–43.

[39] Coppola T et al. A sustainable electrical interface to mitigate emissions due to power supply in ports. Renew Sustain Energy Rev 2016;54:816–23.

[40] Ballini F, Bozzo R. Air pollution from ships in ports: the socio-economic benefit of cold-ironing technology. Res Transport Bus Manage 2015.

[41] Izaguirre-Alza P et al. EU-CargoXpress: wind propulsion concept. Proc – Soc Behav Sci 2012;48:1314–23.

[42] Li Q et al. A study on the performance of cascade hard sails and sail-equipped vessels. Ocean Eng 2015;98:23–31.

[43] Majewska K et al. Experimental method of strain/stress measurements on tall sailing ships using Fibre Bragg Grating sensors. Appl Ocean Res 2014;47:270–83.

[44] Cullinane K, Bergqvist R. Emission control areas and their impact on maritime transport. Transport Res Part D – Transp Environ 2014;28:1–5.

[45] Fet AM, Sørgård E. Life cycle evaluation of ship transportation – development of methodology and testing. Aalesund College (HiA) in Cooperation with Det Norske Veritas (DNV) (HiA 10/B101/R-98/008/00); 1998. p. 32.

[46] Johnsen T, Fet AM. Screening life cycle assessment of M/V color festival. Report; 1999.

[47] Fet AM, Michelsen O, Johnsen T. Environmental performance of transportation – a comparative study. Norway: Norwegian University of Science and Technology, Helge Gravås; 2000. p. 103.

[48] Fet AM. Environmental reporting in marine transport based on LCA. Proc IMarEST J Mar Des Oper 2002:1476–556.

[49] Schmidt JH, Watson J. Eco Island Ferry: comparative LCA of island ferry with carbon fibre composite based and steel based structures. 2.-0 LCA consultants; 2014.

[50] Bengtsson S, Andersson K, Fridell E. Life cycle assessment of marine fuels: a comparative study of four fossil fuels for marine propulsion. Sweden; 2011.

[51] Bengtsson S, Fridell E, Andersson K. Environmental assessment of two pathways towards the use of biofuels in shipping. Energy Policy 2012;44:451–63.

[52] Alkaner S, Zhou P. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. J Power Sources 2006;158(1):188–99.

[53] Strazza C et al. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Appl Energy 2010;87(5):1670–8.

[54] Strand KH, Aarskog KJ. Life cycle assessment of fuel cells onboard ships. In: Department of Marine Technology. Trondheim: Norwegian University of Science and Technology; 2010. p. 1–131.

[55] Zuin S, Belac E, Marzi B. Life cycle assessment of ship-generated waste management of Luka Koper. Waste Manage 2009;29:3036–46.

[56] Jiven K et al. LCA-ship, design tool for energy efficient ships – a life cycle analysis program for ships, final report: 2004-08027; 2004.

[57] Kameyama M et al. Development of LCA software for ships and LCI analysis based on actual shipbuilding and operation. In: Proc 6th Int Conf on Ecobalance; 2005.

[58] Kameyama M, Hiraoka K, Tauchi H. Study on life cycle impact assessment for ships. NMRI (Japan) 2007.

[59] Tincelin T et al. A life cycle approach to shipbuilding and ship operation, in Ship design and operation for environmental sustainability. London: The Royal Institution of Naval Architects; 2007.

[60] Princaud M, Cornier A, Froelich D. Developing a tool for environmental impact assessment and eco-design for ships. Proc Inst Mech Eng Part M – J Eng 2010;224(M3):207–24.

[61] Basurko OC, Mesbahi E. Methodology for the sustainability assessment of marine technologies. J Clean Prod 2014;68:155–64.
[62] Ling-Chin J, Heidrich O, Roskilly AP. Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems. Renew Sustain Energy Rev 2016;59:352–78.
[63] Carlton J, Aldwinkle J, Anderson J. Future ship powering options: exploring alternative methods of ship propulsion. London: Royal Academy of Engineering; 2013.
[64] Mansouri SA, Lee H, Aluko O. Multi-objective decision support to enhance environmental sustainability in maritime shipping: a review and future directions. Transport Res Part E – Log 2015;78:3–18.
[65] Miola A et al. Regulating air emissions from ships. The state of the art on methodologies, technologies and policy options. Joint Research Centre Reference Report, Luxembourg, EUR24602EN, ISBN; 2010: p. 978–92.
[66] Brosnan IG. The diminishing age gap between polar cruisers and their ships: a new reason to codify the IMO Guidelines for ships operating in polar waters and make them mandatory? Mar Policy 2011;35(2):261–5.
[67] Cooper D. Representative emission factors for use in quantification of emissions from ships associated with ship movements between port in the European Community. IVL Swedish Environmental Research Institute Ltd (ENV. C. 1/ETU/2001/0090); May, 2002.
[68] Salmi T et al. Matlab/simulink based modeling of photovoltaic cell. Int J Renew Energy Res 2012;2(2):213–8.
[69] Kobougias I, Tatakis E, Prousalidis J. PV systems installed in marine vessels: technologies and specifications. Adv Power Electron 2013;2013.
[70] Baker J. New technology and possible advances in energy storage. Energy Policy 2008;36(12):4368–73.
[71] Doerffel D, Sharkh SA. Large lithium-ion batteries – a review. In: Electric Vehicle Exhibition (EMA 2006), Aschaffenburg (Germany), 2006, vol. 14; 2006. p. 15.
[72] Wankhede A. The green source of power on ship – shaft generator; 2010. <http://www.marineinsight.com/marine/environment/the-green-source-of-power-shaft-generator/> [cited 2015 18 January].
[73] Skvarenina TL. The power electronics handbook – industrial electronics series. USA: CRC Press; 2001.
[74] Swamy M, Schifko S. An improved active front end non-regenerative rectifier system employing a five-limb inductor. In: 2013 IEEE international electric machines & drives conference (IEMDC); 2013.
[75] Hall WJ. Assessment of CO_2 and priority pollutant reduction by installation of shoreside power. Resour Conserv Recycl 2010;54(7):462–7.
[76] Arduino G et al. How to turn an innovative concept into a success? An application to seaport-related innovation. Res Transport Econ 2013;42(1):97–107.
[77] Gibbs D et al. The role of sea ports in end-to-end maritime transport chain emissions. Energy Policy 2014;64:337–48.
[78] Environmental management – life cycle impact assessment – principles and framework. British Standard; 2006.
[79] Environmental management – life cycle impact assessment – requirements and guidelines. International Organisation for Standardisation (ISO); 2006.