Energy Conversion and Management 127 (2016) 477–493

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A comparative life cycle assessment of marine power systems

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ARTICLE INFO

Article history:
Received 16 May 2016
Received in revised form 2 August 2016
Accepted 2 September 2016
Available online 15 September 2016

Keywords:
Comparative LCA
Environmental impact
Marine power system
Cargo ship
Relative contribution
Fuel consumption

ABSTRACT

Despite growing interest in advanced marine power systems, knowledge gaps existed as it was uncertain which configuration would be more environmentally friendly. Using a conventional system as a reference, the comparative life cycle assessment (LCA) study aimed to compare and verify the environmental benefits of advanced marine power systems i.e. retrofit and new-build systems which incorporated emerging technologies. To estimate the environmental impact attributable to each system, a bottom-up integrated system approach was applied, i.e. LCA models were developed for individual components using GaBi, optimised operational profiles and input data standardised from various sources. The LCA models were assessed using CML2001, ILCD and Eco-Indicator99 methodologies. The estimates for the advanced systems were compared to those of the reference system. The inventory analysis results showed that both retrofit and new-build systems consumed less fuels (8.28% and 29.7% respectively) and released less emissions (5.2–16.6% and 29.7–55.5% respectively) during operation whilst more resources were consumed during manufacture, dismantling and the end of life. For 14 impact categories relevant to global warming, acidification, eutrophication, photochemical ozone creation and PM/respiratory inorganic health issues, reduction in LCIA results was achieved by retrofit (2.7–6.6%) and new-build systems (35.7–50.7%). The LCIA results of the retrofit system increased in ecotoxicity (1–8%), resource depletion (1–2%) and fossil fuel depletion (17.7–161.9%). Larger magnitude of increase was shown by the new-build system in ecotoxicity (90–93.9%) and fossil fuel depletion (391.3%) as a result of handling additional scrap. Relative contribution of significant components towards environmental impact remained profound for the retrofit system (i.e. more than 84% for all impact categories) and became more prominent for the new-build system (approximately 99% for 18 impacts). For retrofit and new-build systems respectively, changes in fuel consumption quantity by ±10% and ±20% varied (i) ecotoxicity and land use by no means, (ii) fossil fuel depletion by 0.95–1.50 and 4.81–5.01 times assessed by CML2001 (or 0.95–1.50 and 5.12–5.32 times assessed by Eco-Indicator99); and (iii) the remaining impact categories by 0.65–1.37 and 0.34–0.92 times. The new-build system showed the greatest mitigation potential in 18 impact categories. The retrofit system was more environmentally friendly than the reference system. Appropriate life cycle management was warrant to avoid burden shifting whilst alleviating the environmental burdens at the same time.

1. Introduction

Marine transport enabled more than 80% of international trade [1] at the expense of emitting substantial quantity of emissions. For instance, it was estimated that 938 Tg of global carbon dioxide (CO_2) and 961 Tg of CO_2-equivalent greenhouse gas (GHG) emissions were respectively released by marine transport in 2012 [2]. Although it only represented 2.1–2.2% of global emissions, it presented a persistent issue, as the figures could be underestimated [3] and more seriously, increased up to 250% in 2050 compared to 2007 [4]. As such, the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI *Regulations for the Prevention of Air Pollution from Ships* (which covered 18 regulations from application to fuel oil availability and quality) was established by the International Maritime Organisation (IMO) as the strategy to mitigate shipping emissions. As clearly stated in Regulations 13 and 14, a number of thresholds were proposed and enforced (or would be enforced in the near future) on shipping emissions released by marine diesel engines installed onboard ships, in particular nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM). Ships transiting in the Emission Control Areas (ECAs) had been or would be subject to stricter requirements. The ECAs designated for these emissions included Baltic

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http://dx.doi.org/10.1016/j.enconman.2016.09.012
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Nomenclature

Abbreviations

AC	alternating current
BTL	biomass-to-liquid
CO	carbon monoxide
CO_2	carbon dioxide
CTUe	comparative toxic unit for ecosystems
DALY	disability-adjusted life year
DC	direct current
DCB	dichlorobutane
ECAs	Emission Control Areas
EEDI	Energy Efficiency Design Index
HFO	heavy fuel oil
GHG	greenhouse gas
GTL	gas-to-liquid fuel
HC	hydrocarbons
ILCD	International Reference Life Cycle Data System
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LB-CH_4	liquefied bio-methane
LBG	liquefied biogas
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
LNG	liquefied natural gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	marine fuel oil
MGO	marine gas oil
NMVOC	non-methane volatile organic compound
NO_x	nitrogen oxides
PDF	Potentially Disappeared Fraction
PM	particulate matter
PSO	Particle Swarm Optimisation
PTO/PTI	power-take-off/power-take-in
PV	photovoltaic
RME	rapeseed methyl ester
RoPax	Roll-on/Roll-off passenger
RoRo	Roll-on/Roll-off
SEEMP	Ship Energy Efficiency Management Plan
SO_x	sulphur oxides
VFDs	variable frequency drives

Symbols

CF	characterisation factor
F	distribution and exposure
I	indicator result of an impact category
m	mass, kg
P	potential risk or likelihood
S	severity factor

Subscripts

E	environmental media
endpoint	endpoint approach
i	substance
midpoint	midpoint approach
n	number of substances
R	exposure routes

Sea, North Sea, North American and Caribbean Sea. Ships were obliged to meet the thresholds by switching to low-sulphur fuels or employing an alternative technique, as indicated in Regulation 4. In addition, the measure of Energy Efficiency Design Index (EEDI) for new ships and the implementation of the Ship Energy Efficiency Management Plan (SEEMP) for all ships had become mandatory since 2013 [5] – which presented a challenge to maritime industry.

Container ships, tankers, LNG carriers, bulk carriers, passenger and cargo vessels such as Roll-on/Roll off (RoRo) and RoRo passenger ships (RoPax), as illustrated in Fig. 1, were common examples of cargo ship categories. The power system onboard a cargo ship provided main and auxiliary power. The former enabled ship propulsion and the latter provided electricity for ship services, e.g. heating, refrigeration, fresh water, lighting, ventilation and pumps. Power systems differed from ship to ship [6], in terms of types and designs. They included diesel mechanical, steam turbine mechanical, nuclear-powered steam turbine mechanical, gas-turbine electric, diesel-electric, all-electric (also referred to as full-electric, integrated electric or integrated full-electric), combined and hybrid systems. Mechanical systems were the conventional design for cargo ships, where power was generated separately from different prime movers. Prime movers that were conventionally applied included diesel, gas and dual-fuel engines, steam and gas turbines as well as nuclear reactors. For most cargo ships, diesel engines were most widely applied. Steam turbines were mainly employed onboard LNG carriers. Applications of other prime mover types were relatively limited for cargo ships but more common for other ship types. For example, gas turbines were commonly used in combined power systems for naval ships whilst nuclear was by and large for warships and icebreakers. Interest in all-electric power systems has been growing, which generated three-phase electricity based on power demand for optimal performance to simultaneously supply electricity to both propulsion drives and all auxiliaries [7]. All-electric power systems involved alternating current (AC) and/or direct current (DC) distribution. When an AC distribution system (which was more common) was considered, an all-electric power system would generally consist of prime movers, synchronous generators, switchgears, transformers, power electronics converters, electric motors and propellers. The prime movers employed for an all-electric power system could be of various sizes of conventional propulsion technologies, including internal combustion engines [8], gas turbines [9] or diesel engines combined with gas turbines [10]. The synchronous generator would be coupled to and powered by the prime mover to generate AC power [8], which was then adjusted by transformers and converted by converters before being used (i) by the electric motors to drive the propellers and (ii) for auxiliaries and hotel loads. The speed of the prime movers and electric motors was strategically controlled [9] for optimal power output. An all-electric power system was demand based as different (and only the necessary) prime movers would be selectively operated for optimal efficiency [7].

To date, marine transport research had focussed on energy consumption and/or emissions, marine diesel engines, operational strategies, innovative technologies for efficiency improvement, alternative system designs and other strategies in relation to decision making, economics and legislation. For instance, relationships between emissions and sailing modes [12], ship types and sizes [13], composition of exhaust [14], energy and emissions that would be released from marine fuel combustion [15] and methods that could be applied for the estimate [16] were previously investigated. Research focussing on marine diesel engines covered maintenance [17], injection pressure [18], charged air temperature and pressure [19]. In terms of operational strategies, existing studies analysed sailing speed optimisation [20], relevant taxonomy

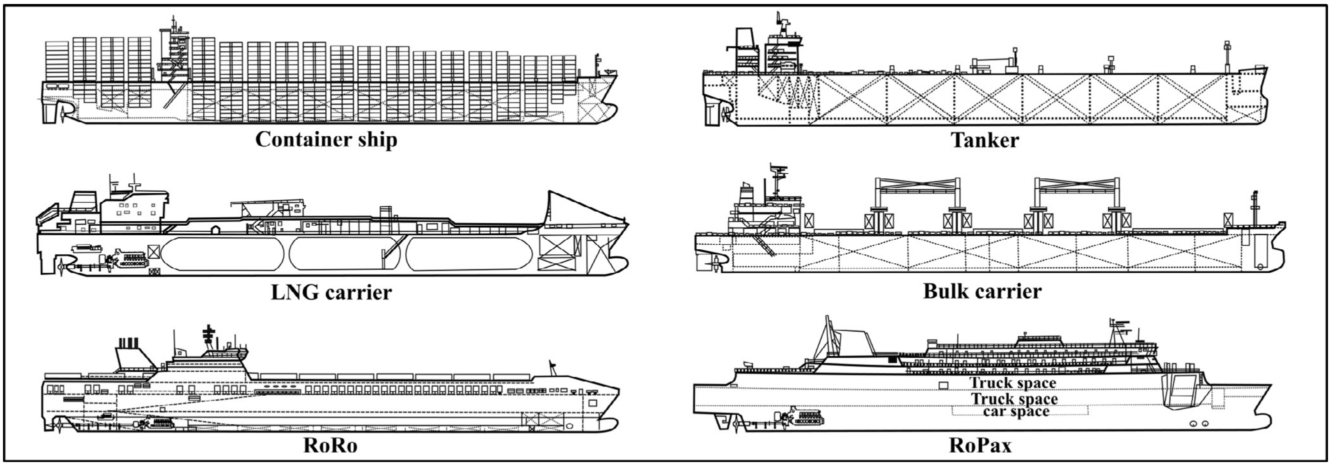

Fig. 1. Generic structure of some marine vessels adopted from [11].

and parameters [21], waiting time in port [22] and energy efficiency which took these factors into account [23]. Research which spotlighted innovative technologies included, but not limited to, waste heat recovery via the employment of combined steam and organic Rankine cycle by diesel engines [24], integration of fuel cells into marine power systems [4] and comparison with other alternatives [25], photovoltaic (PV) systems for marine application [26], wind propulsion using towing kites, Flettner rotors or hard sails [27,28], cold ironing for on-shore power supply when ships were in port [29,30], and batteries for hybrid propulsion systems [31]. Examples of research on alternative system designs included [32,33] which reviewed the employment of gas and steam turbines combined cycles for large ships and [34] which investigated a boil-off gas reliquefaction system for liquefied natural gas (LNG) carriers. Other supporting tools included frameworks for efficiency enhancement [35] and trade-off analysis between fuel sources and technologies [36], algorithm for bunker fuel management at optimum speed and minimum cost [37] as well as legislation consideration [38], to name a few.

Due to the emergence of innovative technologies, marine power system designs were no longer limited to conventional configurations i.e. diesel mechanical system for most cargo ships and steam turbine mechanical system for LNG carriers. To comply with MARPOL, ship owners had started to consider the environmental performance of marine power systems in choosing a design. As such, life cycle assessment (LCA) had been applied in the marine context to scrutinise marine transport from an environmental perspective. International standards on LCA were established by the International Organisation for Standardisation (ISO). Referred to as ISO 14040 and 14044 [39,40], the Standards defined fundamental principles and requirements involved in performing an LCA study. The 4 iterative LCA phases covered goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation. The goal of an LCA study should tell why, for whom, for what and whether or not. This could be done by clearly defining the reason of performing the study, the targeted audience, the intended application and any plan to use the results in comparative assertions and disclose them to the public. The scope of the study should define what was to be studied, what methodology or approach was to be applied and what requirements were to be met. These included the product system, function, functional unit, reference flow, system boundary, allocation, assumptions, data quality, impact categories, LCIA methodologies, limitations, critical review (if any) and report format. Comparison of alternative product systems could only be made provided the systems delivered the same function based on defined reference flows with a common functional unit. During LCI, materials, energy flows and products involved throughout the defined life cycle phases were compiled from various sources as input and output flows. Assumptions were made as the tasks progressed, when necessary. In relation to LCIA, ISO 14040 and 14044 had established *selection, classification and characterisation* together with *normalisation*, *grouping* and *weighting* respectively as mandatory and optional LCIA elements. During *selection*, impact categories, category indicators and characterisation models that were recognised internationally and related to the product system under study were selected. This was followed by *classification*, where LCI results were assigned to appropriate impact categories. Category indicator results (also referred to as LCIA results) for individual impact categories were estimated by *characterisation*. The indicator results were the aggregated products of the LCI results and the characterisation factors. Optionally, *normalisation* was performed in which category indicator results were compared to a reference. *Grouping* was involved if impact categories were organised based on a defined criterion. When weighting factors were derived from value choices and applied to the indicator results or normalised results, *weighting* was applied, in which the products were summed up to present an aggregated score across all impact categories. LCI and LCIA results were analysed during life cycle interpretation to identify significant issues, followed by an evaluation on consistency and completeness of the study and sensitivity of the results prior to drawing conclusions and making recommendations.

In relation to LCA applications in the marine context, the scope that had been explored included software [41–45], shipping [46–49], marine fuels [50,51], emission abatement options [52], ship-generated waste [53], power technologies [54–56], marine power systems [57,58] and LCA framework [59,60]. The software was designed to estimate life cycle burdens from ship operation during design [41], assist the development of life cycle inventory [42] and LCA methodology [43], provide an eco-design tool which integrated with environmental impact assessment [44], and allow for environmental, economic and safety assessments [45]. The research basis of an environmental impact assessment for ships (which covered system boundaries and methods) [46] as well as trends and requirements for an environmental report [47] were presented. Also, the environmental impact of ships was assessed at design phase without performing detailed LCA [48] whilst the impact of 2 ferries made of steel and polymer composite respectively was estimated by [49]. In terms of marine fuels, heavy fuel oil (HFO), marine gas oil (MGO), gas-to-liquid fuel (GTL), and

LNG with/without emission abatement technologies were compared [50]. This was followed by a study on biofuels including rapeseed methyl ester (RME), biomass-to-liquid (BTL), liquefied biogas (LBG) and liquefied bio-methane (LB-CH_4) [51]. In relation to marine emission abatement options, an open-loop seawater scrubber, a close-loop freshwater/sodium hydroxide scrubber and a dry scrubber were investigated [52]. Onshore units used for treating bilge water, waste water, solid waste and kitchen waste were also assessed [53]. The conventional diesel engine was compared separately with a molten carbonate fuel cell run by low sulphur fuel [54], a solid oxide fuel cell run by methanol [56], a molten carbonate fuel cell and a gas engine [55]. The environmental benefits of retrofitting a conventional system [57] and the environmental impact of a new-build system [58] were respectively reported. LCA frameworks were also presented, which focussed on shipping emissions due to hull, engines and boilers [59] and marine PV systems [60].

Considering the diversity in cargo ship types, fuel types and sailing profiles, previous LCA studies were relatively limited. In particular, the power systems assessed in [57,58] were limited to a retrofit system and a new-build system respectively. Despite of growing interest in advanced power systems for possible improved sustainability, the environmental benefits of integrating innovative technologies into retrofit and new-build power systems had not yet been compared in a single study. It was uncertain which power system would be more environmentally friendly, and therefore knowledge gaps existed. The study aimed to verify the benefits of advanced power systems based on comparison with a reference system from an environmental perspective in a comparative LCA study. The objectives were to compare LCI and LCIA results of the power systems, and investigate relative contribution of significant components and the influence of fuel consumption quantity.

2. Methods

As LCA case studies applied in this work involved massive system boundaries, a bottom-up integrated system approach was adopted. The reason of carrying out this comparative LCA study was to verify the environmental performance of selected marine power systems when compared to a reference system. The targeted audience included, but not limited to, maritime stakeholders, in particular ship owners, operators, policy makers, and LCA practitioners. The application was to justify the employment of innovative power systems as a sustainable approach to mitigate the environmental burdens of marine transport and furthermore assist maritime stakeholders in their decision making. Based on the findings, the study intended to present comparative assertions to the public via journal publication.

An existing conventional power system onboard an intra-European Ro-Ro cargo ship was chosen as the reference system for this comparative study. The designs of the systems under study were illustrated in Fig. 2 and details of individual components were summarised in Table 1. The conventional system consisted of 4 main diesel engines which were connected to 2 gearboxes respectively to drive 2 propellers, in addition to 2 shaft generators, 2 bow thrusters, 2 thermal oil boilers and 2 economisers. For propulsion purpose, 2 diesel engines were run continuously at constant speed by burning (i) HFO when the ship was transiting at sea and marine fuel oil (MDO) 0.5–1 h before entering and after leaving the port prior to the enforcement of SO_x control in November 2007; and (ii) all MDO after the enforcement. Each bow thruster was run by a built-in motor for manoeuvring purpose. The auxiliary power demand of 650 kW and 850 kW when the ship was in port and at sea respectively was met by running the auxiliary generators – one burned HFO and MDO in a similar way as diesel engines and the other burned MDO only – together with 2 boilers which burned MDO only. Exhaust gas from diesel engines was directed to 2 economisers and used for pre-conditioning fuels. The shaft generators were not in use due to low power demand. NOx emission was controlled via water injection technique.

The following retrofit and new-build power systems were investigated in this comparative study:

(i) The retrofit power system integrated lithium ion batteries, cold ironing, power-take-off/power-take-in (PTO/PTI) and PV systems into the existing power system with the use of frequency converters and variable frequency drives (VFDs). The integration took place after operating the existing power system for 10 years, where the retrofit system would continue to operate for 20 years. When the ship was at sea, main power was mainly met by running 2–4 diesel engines which burned MDO, and augmented by energy from PV and lithium-ion battery systems. The auxiliary load was partially supplied by an auxiliary generator and a shaft generator (in PTO mode when the shaft generator was connected to diesel engines); or fully supplied by auxiliary generators when the shaft generators were (in PTI mode) driving the propellers. During slow steaming, only one propeller would be powered by PTI. During manoeuvring, mooring and waiting in port, all diesel engines and auxiliary generators were shut down; thrusters were governed by frequency converters to operate at variable speeds; and on-shore power was supplied via cold-ironing to run one of the boilers for hotel services and charge the battery systems.

(ii) The new-build all-electric power system employed diesel gensets (as prime movers which burned MDO only), cold–ironing, PV and lithium ion battery systems as well as power electronics such as transformers, VFDs, AC–AC converters, inverters and rectifiers. At sea, 3 or more gensets and at least 1 propeller driven by a motor would be run for power generation and ship propulsion. Energy was generated by PV systems during day time. The generated power was taken and distributed by a main switchboard via distribution bus bars to consumers for propulsion, heating, cooling and other hotel services. Battery systems would supplement power supply during peak loads or store up surplus energy, if there was any. During manoeuvring and mooring, thrusters were driven by their motors where power demand was met mainly by running two gensets. In port, onshore power would supply electricity via cold-ironing for hotel services, cargo equipment, deck machinery and battery charging. Power electronics were in use in line with their connecting propellers, thrusters, gensets, onshore power supply, PV or battery systems.

The power systems were designed by research consortium involved in the project based on (i) the need to meet stricter regulations set by IMO; (ii) technical consideration in terms of innovation and operation; (iii) interest of maritime stakeholders; and (iv) data availability. The systems not only represented the state-of-the-art designs (which strategically incorporated a range of advanced technologies to improve operational performance during manoeuvring and transiting) but also had the potential for commercial applications. The power systems served the same function i.e. supply energy required for propulsion and operation of the RoRo cargo ship. A common functional unit was defined i.e. operation of the power system for the same RoRo cargo ship travelling on regular routes over 30 years. Uniformity in cargo ship type, function, business route and lifespan led to a common reference flow i.e. one power system required by the ship for 30-year operation. In this comparative study, system boundary included all

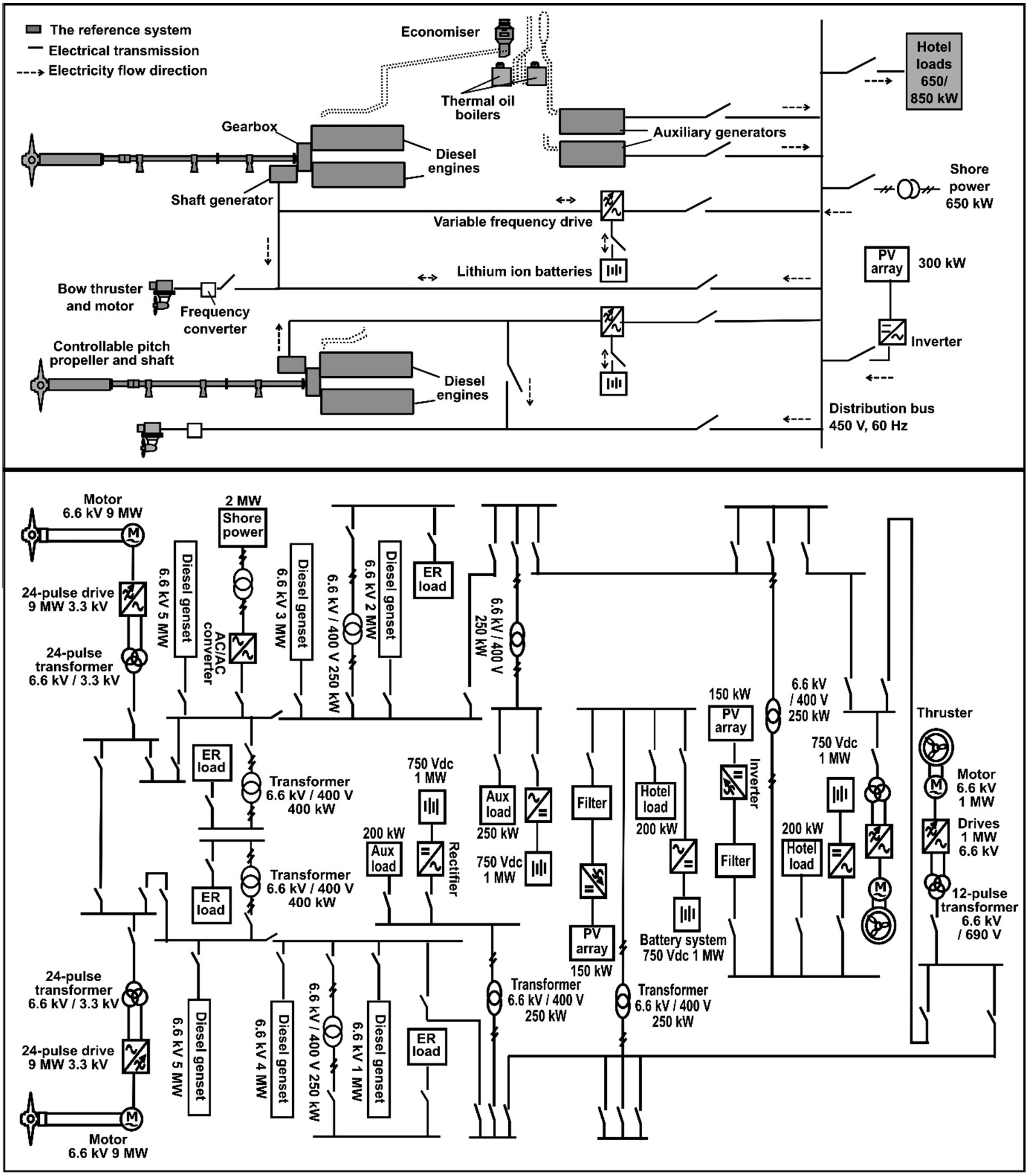

Fig. 2. The configurations of the reference (top, covering components in grey boxes only), retrofit (top, including all components) and new-build (bottom) systems.

components incorporated into each power system as well as their replacement components (which were necessary due to their shorter lifespans). The life cycle considered for each component covered the acquisition of energy and raw materials, manufacture, operation, maintenance and the end of life, as illustrated in Fig. 3. Allocation was avoided via system expansion.

For the reference and retrofit systems, background data were collected and standardised from various sources, and supplemented by commercial database, Ecoinvent database (version 2.2), provided background data from other sources were not available, as applied in [57]. For the new-build system, data for the manufacturing processes were standardised based on relevant inputs from manufacturers (on the basis of a non-disclosure agreement), expert judgement of the industrial consortium and Ecoinvent database as applied in [58]. Real-time operational data of the reference ship were provided by the ship operator and used by research partners to obtain optimised operation profiles for both retrofit and new-build advanced systems based on Simplex and Particle Swarm Optimisation (PSO) simulation approaches. The simulation results and emission factors reported in [61] were used to estimate the primary data required for this comparative study i.e. fuel consumption and emission release during operation.

Table 1
Details of individual components integrated into the reference, retrofit and new-build power systems.

Component	Details	
Prime movers and auxiliary generators (if relevant)	R*	Diesel engines: Sulzer 8ZA40S, 4-stroke, in-line, medium speed, 510 rpm, non-reversible, 5760 kW, 78,000 kg, 30 years each, 4 units; Auxiliary generators: MAN B&W 7L28/32H, 4-stroke, in-line, 750 rpm, 1563 kW, 39,400 kg, 30 years each, 2 units
	N	Diesel gensets: Wärtsilä W9L32E, 5 MW, 47,000 kg, 2 units; W8L32E, 4 MW, 43,500 kg, 1 unit; W6L32E, 3 MW, 33,500 kg, 1 unit; W6L26, 2 MW, 17,000 kg, 1 unit; and W6L20, 1 MW, 9300 kg, 1 unit, 30 years (all)
Shaft generators	R*	AvK DSG 88M1-4, 2125 kVA, 2125 kg, 30 years each, 2 units
Gearboxes	R*	Renk AD NDSHL3000, output speed of 130 rpm at a reduction ratio of 3.923:1, 510 rpm, 5760 kW, 1415 kg, 30 years, 2 units
Propellers and shafts	R*, N	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, 2 units
Propulsion motors	N	Hyundai Type HHI/HAN3 245-16, brushless, synchronous, 8900 kW, 15–125 rpm, 3 phases, 16 poles, 110,000 kg, 30 years, 2 units
Bow thrusters and motors	R*	Lips CT175H, transverse, with built-in motors, of controllable pitch standard design propeller diameter of 1.75 m, 1465–1755 rpm (input), 316–379 rpm (output), 50–60 Hz, 1000 kW h, 5900 kg, 30 years, 2 units
	N	Wärtsilä CT/FT 175 M controllable pitch, standard design, 60 Hz, 1170 rpm, 995 kW, 5600 kg, 30 years, 2 units; Hyundai Type HHI/HRN7 567-6, squirrel cage, induction thruster motors made by 1250 kW, 1200 rpm, 3 phases, 6 poles, 630 V, 60 Hz, 75,000 kg, 30 years, 2 units each
Thermal oil boilers	R*	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, 2 (plus 2) units
Economisers	R*	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, 2 (plus 2) units
Frequency converters	R	ABB ACS800-07, standard cabinet-built drive, 500 V, 1000 kW, 1410 kg, 10 years, 2 (plus 2) units
AC-AC rectifiers	N	SINAMICS G150-42-2EA3, 2150 kW, 3.6 m × 2.0 m × 0.6 m, 3070 kg, 20 years, 1 (plus 1) unit
VFD	R	Ingeteam™ LV4F-32-131WA-348 + Z, active front end, water cooled cabinet, 480 V, 1774 kVA, 3600 kg, 10 years, 2 (plus 2) units
	N	ABB MEGADIVE LCI drives A1212-211N465 connecting propulsion motors, air-cooled, 9100 kW, 10,000 kVA, 7000 kg, 15 years, 2 units; Altivar ATV1200-A1190-4242 medium voltage VFDs connecting thruster motors, 995 kW, 1190 kVA, 4.06 m × 1.40 m × 2.67 m, 5000 kg, 15 years, 2 units
PV systems	R	1212 units of Kyocera KD245GX-LPB module, 1994 m^2, 25,452 kg, 20 years, 1 single-array system; Schneider Electric GT 250–480 inverter, 300–480 V, 250 kW AC, 2018 kg, 10 years, 1 (plus 1) unit
	N	Fixed tilted planes 2-array PV system, each consisted of 598 modules manufactured by Kyocera (Type KD245GX-LPB, 245 Wp per module at standard test conditions), 13 modules arranged in series per string for 46 strings occupying 984 m^2 supplying 147 kWp, 21 kg per module, 30 years, 2 units; Schneider Electric GT100-208 inverter, 300–480 V, 100 kW AC, 1.7 m × 1.2 m × 1.9 m, 1361 kg, 10 years, 1 (plus 2) inverter per array
Lithium-ion battery systems	R	Seanergy® LiFePO4 VL 41 M Fe 265 W h/l, rechargeable, 2 MW h, 21,900 kg with cabinets (or 16,800 kg without cabinets), 20 years each, 2 units
	N	Seanergy® battery system Type LiFePO4 VL 41 M Fe 265 W h/l, phosphate graphite, 8 battery racks contributing to 1 MW h per system, each rack (composed of 14 modules and each module consisted of 14 cells) was 6 m × 8 m × 12–23 m and 730 kg or 560 kg with or without cabinet, 20 years, 4 (plus 4) units; Sitras® REC rectifier per battery system, 750 V, 0.8 m × 2.2 m × 1.4 m, 850 kg, 10 years, 1(plus 2) unit per battery system
Transformers	R, N	For cold ironing: An ABB RESIBLOC® cast-resin dry transformer, 1000 kVA, 3150 kg, 20 years, 1 (plus 1 for new-build system) unit
	N	TRAFOTEK, 24-pulse transformers connecting propulsion motors, 2 units, each consisted of 2 (plus 2) units of 12-pulse, dry cast resin transformers, 6890 kVA, 6600 V, 60 Hz, 3.25 m × 2.56 m × 1.68 m, 10,900 kg, 20 years TRAFOTEK, 12-pulse, dry transformers connecting thruster motors, made by 1750 kVA, 6600 V, 60 Hz, 2.63 m × 1.99 m × 1.38 m, 3600 kg, 20 years, 2 (plus 2) units ABB RESIBLOC® distribution transformers, 400 kVA under no load loss condition, 1.66 m × 1.17 m × 1.71 m, 1580 kg (or 1420 kg without casing); ABB RESIBLOC® transformers, 250 kVA under no load loss condition, 1.51 m × 1.12 m × 1.66 m and 1220 kg (or 810 kg without casing), 15 years, 6 (plus 6) units

R*: Reference and retrofit power systems; R: Retrofit power system; N: New-build power system. Details for all components, with the exception of PV systems, were presented as individual components. The additional number of components required for replacement was shown in brackets.

For dismantling and the end of life of non-metallic scrap, relevant Ecoinvent datasets were adopted. Data applied for the end of life of metallic scrap were standardised from Ecoinvent database and literature in line with the scrap types i.e. iron and steel [62,63], stainless steel scrap [64,65], aluminium [66,67], copper [63,68,69], lead [63,69,70], nickel [63,69,71], zinc, brass and bronze [69,72]. Data adopted from Ecoinvent database were not detailed here due to the terms of use.

Assumptions were made consistently in each case, following the guidelines of ISO14044 i.e. "comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent". In the study, it was assumed that (i) the same business routes and the operational profiles were valid for 30 years; (ii) lubricating oil was changed for every 1500 operating hours for diesel engines, gensets and auxiliary generators; (iii) materials and manufacture process of economisers were similar to those of boilers; (iv) diesel engines and shaft generators that were not in use would be refurbished and reused; (v) any part of the diesel engines, gensets and auxiliary generators that were in a satisfactory condition would be reused as spare parts whilst the remaining materials would be recycled or disposed to incineration plants or landfill following a reuse-recycling-incineration-landfill ratio of 3:3:2:2; and (vi) scrap from other components would be recycled, disposed to incineration plants or landfill, 33.3% each.

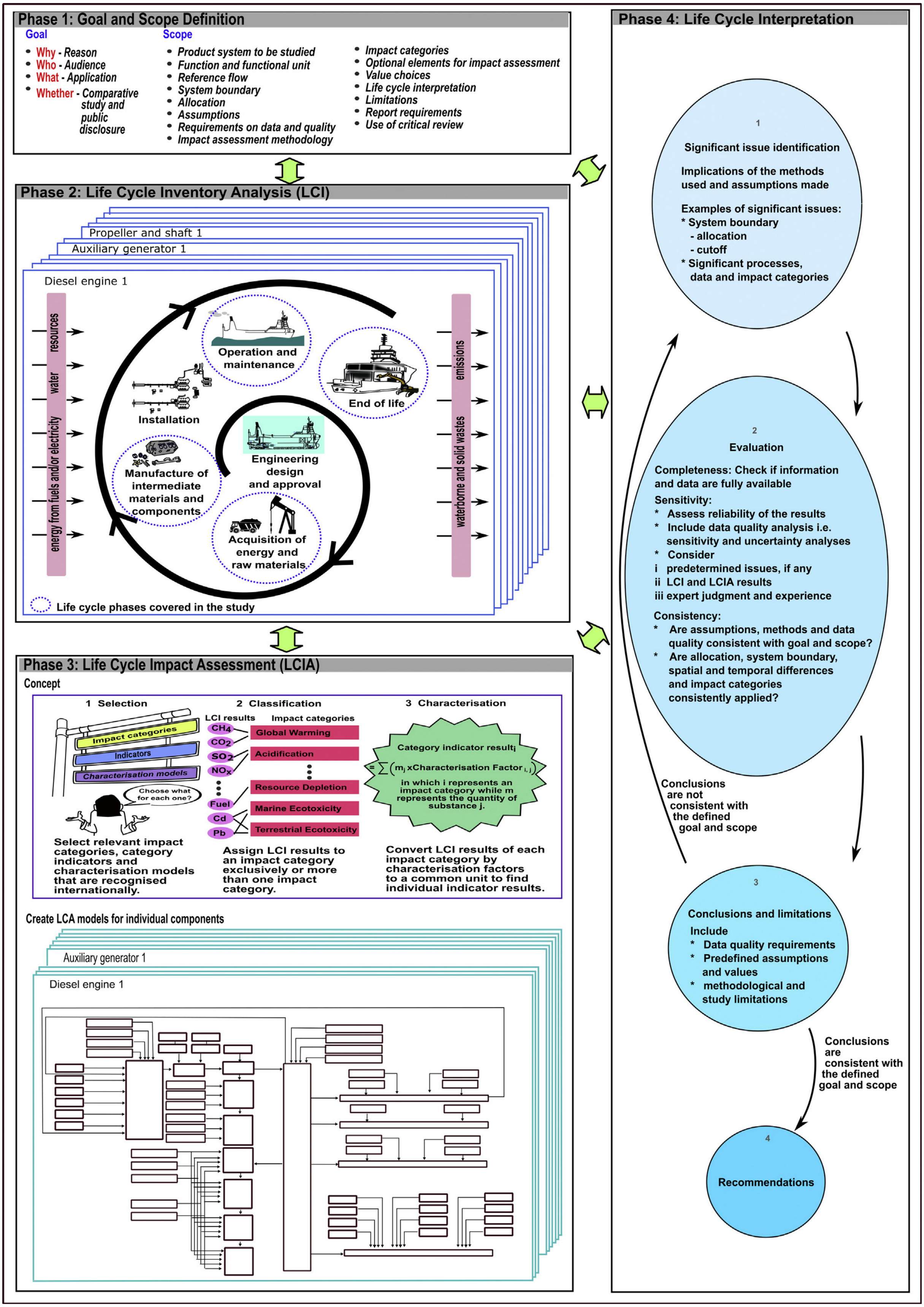

Fig. 3. LCA concept applied in this study in accordance with ISO 14040.

Environmental impact was indicated by the indicator results of individual impact categories estimated using selected LCIA methodologies based on midpoint and/or endpoint approaches. The mathematic formula could be generalised as $I = \sum CF_i m_i$, where *I* was the indicator result of an impact category, *CF* was the corresponding characterisation factor and *m* was mass of a substance (*i*). For both midpoint and endpoint approaches, the underlying mathematic concepts of LCIA methodologies were explained by [73]. The formulas could be presented as $I_{midpoint} = \sum F_{ERi}\, P_{Ri}\, m_{Ei},\ i = 0, \ldots, n$ and $I_{endpoint} = \sum F_{ERi}\, P_{Ri}\, S_{ERi}\, m_{Ei}$, $i = 0, \ldots, n$ respectively for *n* substances distributing across various environmental media (*E*) such as air, freshwater, sea water and soil via different exposure routes (*R*), where *F* was the distribution and exposure of *m* kg of substance *i*, *P* was the potential risk or likelihood of imposing an effect, and *S* was the severity factor e.g. years of life lost per affected person. Approaches applied in estimating *F*, *P* and *S* varied from one characterisation methodology to another, which might involve surveys, empirical/experimental data, advanced statistics and numerical/stochastic simulation. In this study, an assessment using more than one methodology was necessary for comprehensive understanding as none of the LCIA methodologies had covered the full set of relevant impact categories. The midpoint-oriented CML2001 methodology differentiated marine, freshwater and terrestrial ecotoxicity potential and estimated human toxicity potential. The best practice recommended by the International Reference Life Cycle Data System (ILCD) distinguished between marine and terrestrial eutrophication and was more relevant in the European context. The assessment was complemented by the endpoint-oriented Eco-Indicator99 methodology in a similar line of thought with [74,75], which advocated that both midpoint and endpoint approaches should be consistently presented in series or parallel in an LCA framework (i.e. LCA application in this case). The methodological concepts of CML2001, ILCD and Eco-Indicator99 were detailed in [76–78]. LCIA results for 26 impact categories estimated using CML2001, ILCD and EcoIndicator99 were labelled as I–XXVI in this article as in the following for brevity and consistency:

I CML2001: *Marine Aquatic Ecotoxicity Potential*, kg 1, 4-dichlorobutane (DCB) equivalent.
II CML2001: *Global Warming Potential*, kg CO_2 equivalent.
III CML2001: *Global Warming Potential, excluding Biogenic Carbon*, kg CO_2 equivalent.
IV CML2001: *Freshwater Aquatic Ecotoxicity Potential*, kg 1, 4-DCB equivalent.
V CML2001: *Human Toxicity Potential*, kg 1, 4-DCB equivalent.
VI CML2001: *Acidification Potential*, kg SO_2 equivalent.
VII CML2001: *Eutrophication Potential*, kg phosphate equivalent.
VIII CML2001: *Abiotic Depletion of Fossil*, MJ.
IX CML2001: *Photochemical Ozone Creation Potential*, kg ethene equivalent.
X CML2001: *Terrestric Ecotoxicity Potential*, kg 1, 4-DCB equivalent.
XI ILCD: *Ecotoxicity for Aquatic Freshwater, USEtox (recommended)*, comparative toxic unit for ecosystems (CTUe).
XII ILCD: *IPCC Global Warming, including Biogenic Carbon*, kg CO_2 equivalent, where IPCC was the acronym for Intergovernmental Panel on Climate Change.
XIII ILCD: *IPCC Global Warming, excluding Biogenic Carbon*, kg CO_2 equivalent.
XIV ILCD: *Terrestrial Eutrophication, Accumulated Exceedance*, mole of nitrogen equivalent.
XV ILCD: *Acidification, Accumulated Exceedance*, mole of hydrogen ion equivalent.
XVI ILCD: *Photochemical Ozone Formation, LOTOS-EUROS Model, ReCiPe*, kg non-methane volatile organic compound (NMVOC).
XVII ILCD: *Total Freshwater Consumption, Including Rainwater, Swiss Ecoscarcity*, kg.
XVIII ILCD: *PM / Respiratory Inorganics, RiskPoll*, kg $PM_{2.5}$ equivalent.
XIX ILCD: *Marine Eutrophication*, *EUTREND model, ReCiPe*, kg nitrogen equivalent.
XX ILCD: *Resource Depletion, Fossil and Mineral, Reserve Based*, CML2002, kg antimony equivalent.
XXI Eco-Indicator99: *Ecosystem Quality – Acidification/Nutrification*, $PDF * m^2 * a$ (where PDF was the shortened form of Potentially Disappeared Fraction).
XXII Eco-Indicator99: *Ecosystem Quality – Ecotoxicity*, $PDF * m^2 * a$.
XXIII Eco-Indicator99: *Resources – Minerals*, MJ surplus energy.
XXIV Eco-Indicator99: *Resources – Fossil Fuels*, MJ surplus energy.
XXV Eco-Indicator99: *Ecosystem Quality – Land-Use*, $PDF * m^2 * a$.
XXVI Eco-Indicator99: *Human Health – Respiratory (Inorganic)*, DALY (where DALY was the shortened form of disability-adjusted life year).

LCIA was performed using commercial software i.e. GaBi (Version 6). CML2001, ILCD and EcoIndicator99 methodologies, relevant impact categories and characterisation factors of individual chemicals were incorporated into the software and ready for use. Modelling principles of the software were explained in [79]. The software was used to create LCA models for individual components of the reference, retrofit and new-build systems, as illustrated in Fig. 3, Phase 3. By running individual LCA models one by one, all input and output flows were "classified" to relevant impact categories for characterisation purpose. For each impact category, the LCIA results of individual components were summed up (i.e. bottom-up approach) to estimate the total environmental impact attributable to individual power systems. Due to time and resource constraints, engineering design and approval, installation and testing, auxiliaries (including switchboards, cables, piping and fuel oil systems), locations of manufacture and recycling sites, transportation (except when existing Ecoinvent datasets were directly applied), material loss, malfunction of components, change in future technology, spatial and temporal differentiation, and impact categories such as thermal pollution, noise disturbance and odour were not addressed, which presented the limitations of the study. Value choices were involved in selecting the ship type and power system designs (based on technical consideration and expert judgement from the research consortium) as well as characterisation models.

The results of LCI and LCIA were analysed based on their magnitude. The impact categories were grouped in line with methodologies and ranked in descending order of their magnitude. Whilst the LCIA results for both systems were compared to the reference ship per individual impact categories, weighting was not performed. During life cycle interpretation, significant issues, such as components and critical processes which resulted in noticeable environmental burdens, were identified. To verify the environmental benefits of the power systems and identify the system which was more environmentally friendly, a comparison was made based on the concept of "relative percentages for the main components" as previously applied by [80], which focused on the contribution of significant components towards individual impact categories. In this study, components that contributed at least 5% of the total mass were defined as significant components. As such, mass was adopted as the cut-off criterion during interpretation.

The results were checked for completeness and consistency with the defined goal and scope. As it was not transparent how impact assessment methodologies were incorporated in the software, the most suitable approach to address uncertainty issue in this study would be scenario analysis – which had been recognised as a method for both uncertainty and sensitivity analyses. In practice, fuel consumption was primarily concerned by industrial practitioners. The influence of fuel consumption on the total LCIA results was therefore investigated by varying the quantity of fuel consumption by 10% less, 20% less, 10% more and 20% more one by one whilst keeping other parameters unchanged. Critical review was conducted internally by partners involved in the project. The LCIA results gained from additional scenarios were analysed for new findings prior to drawing conclusions.

3. Results and discussion

3.1. LCI results

As illustrated in Fig. 4, metallic and non-metallic materials that were consumed by the retrofit and new-build systems but not the reference system included carbon black, graphite, ferrite, silver, epoxy resin, ethylene vinyl acetate, fleece, glass, hexafluorethane, nylon, phthalic anhydride, polyvinylfluoride, polypropylene, polystyrene, polyvinylchloride, acetone, iron(II) sulphate heptahydrate, phosphoric acid, lithium hydroxide monohydrate and sulfuric acid. For other materials illustrated in Fig. 4, an increase was shown (i) by the retrofit system by up to 2 orders of magnitude; and (ii) in most materials consumed by the new-build system with the exception of brass, carbon, cast iron, tin, polyethylene and rockwool, when compared to the reference system. During manufacture, the retrofit system consumed 138.3% more electricity and 6.3–8.1% more HFO, light fuel oil and natural gas compared to the reference system. A different trend was shown by the new-build system i.e. 59.8% more electricity than the reference system (which was less than the quantity consumed by the retrofit system) and 45.0–64.9% more HFO, light fuel oil and natural gas than the reference system (which also exceeded the quantity consumed by the retrofit system). Overall, more materials and energy were involved and consumed in manufacturing components that were incorporated into the retrofit and new-build systems when compared to the reference system, as a result of more components being integrated into the former systems.

Fuel consumption and emissions involved in the operation were illustrated in Fig. 5. A scale of 1 was shown by HFO as a result of no difference between retrofit and reference systems (in line with the conditions defined for energy management modelling). Meanwhile, MDO consumed by the retrofit system was 0.92 times of that of the reference system due to optimised operation as well as the integration of emerging technologies to augment power supply. The analysis showed that less fuel consumed by the retrofit

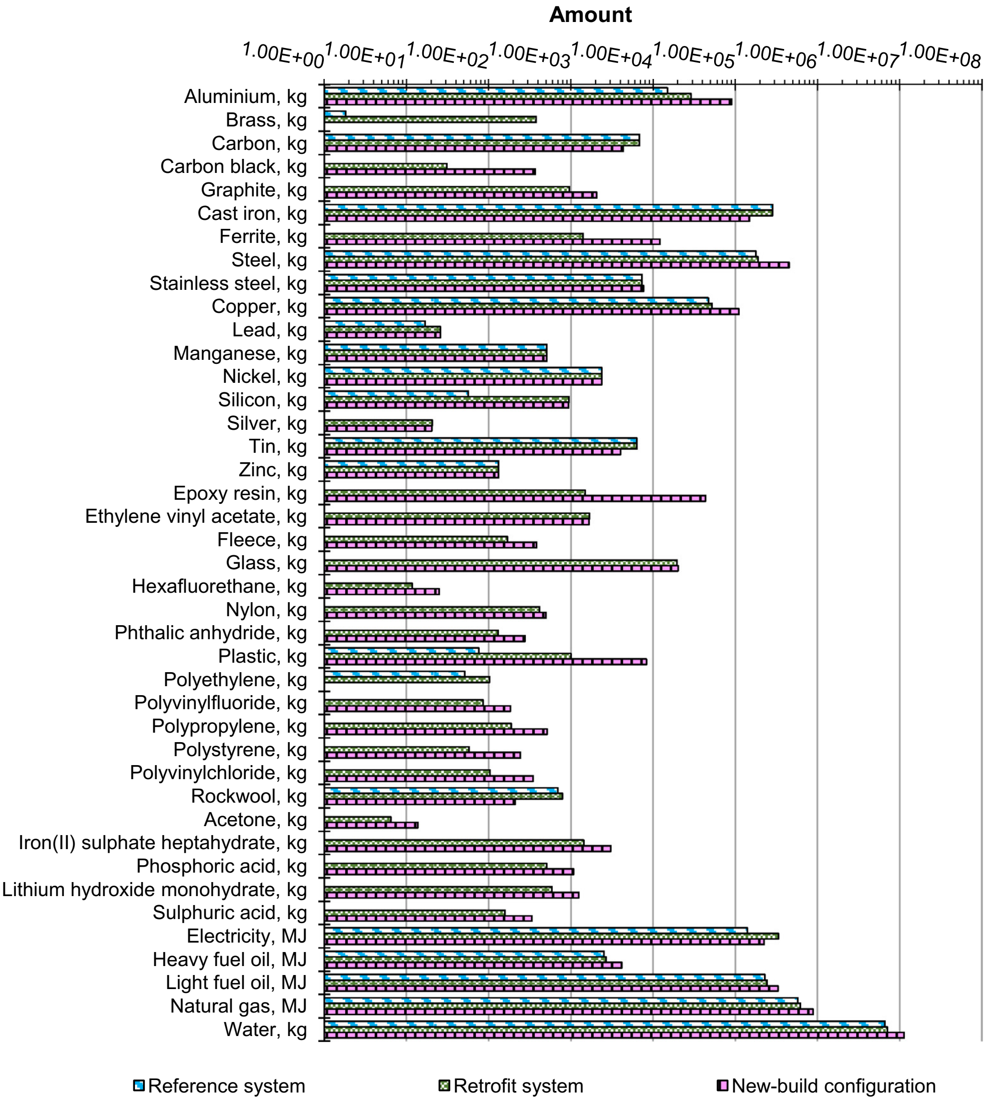

Fig. 4. Comparison of materials consumed by the reference, retrofit and new-build systems during manufacture phase.

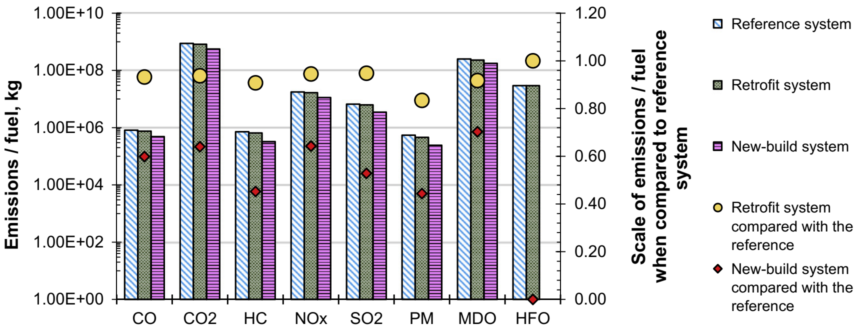

Fig. 5. Total emissions and fuel consumption of both retrofit and new-build systems compared to those of the reference system during operation (in which a scale of 0 indicated no emission or fuel was involved by the system being compared whilst a scale of 0.5 suggested that emission/fuel of the system being compared was 0.5 times of that of the reference system).

system compared to the reference system i.e. by 8.28% would lead to emission reduction by 5.2–16.6%. As such, CO_2, NOx, SO_2, carbon monoxide (CO), hydrocarbons (HC) and PM released by the retrofit system were 0.83–0.95 times of those from the reference system, when the quantity was compared directly. With regard to the new-build system, the least quantity of fuel and emissions was involved i.e. 29.7% less MDO and 100% elimination of HFO compared to the reference system, leading to a 29.7–55.6% of emission reduction. As a result, CO_2, NOx, SO_2, CO, HC and PM released by the new-build system were 0.45–0.70 times of those from the reference system. As a whole system, the new-build system consumed less fuels and released less emissions compared to the retrofit system during operation.

Having said that, a different trend was observed during dismantling and the end of life, as illustrated in Fig. 6. The analysis showed that the retrofit system consumed more coal, light fuel oil, natural gas and electricity than the reference system during dismantling. Similarly, the retrofit system required more resources at the end of life, with the exception of HFO and coal. In both reference and retrofit systems, HFO and coal were required for handling nickel scrap of propellers and thrusters. The same quantity of nickel scrap contained in both systems led to no change in the consumption of coal and HFO during the end of life phase. The increase in other resources varied from small magnitude as shown by energy acquired from blast furnace gas (i.e. 11.7%) to a significant level as shown by coke (i.e. up to 196.8%). Additional coke consumption was required for recycling an extra quantity of steel scrap (i.e. 6.7%) as a result of additional components incorporated into the retrofit system. Natural gas burned at the end of life of the retrofit system was 2.44 times of the quantity required by the reference system. The increased quantity was mainly used in recycling the extra quantity of steel and aluminium scrap (i.e. 92.7% for the latter) as well as disposing additional metallic scrap to landfill. Other resources consumed during dismantling and the end of life were 1–2 times of those required by the reference system. In connection to the new-build system, a reduced consumption of coal, light fuel oil and natural gas during dismantling (i.e. approximately 18%) came along with a slightly higher electricity demand (i.e. 27.8%) when compared to the reference system. The variation was the outcome of diversity in scrap types and quantities of both reference and new-build systems, due to the employment of different components. During the end of life of the new-build system, a greater demand for most resources was observed i.e. 1.47–6.69 times of those consumed by the reference system. Natural gas consumption was found as the mostly consumed resource which showed the highest increase rate i.e. 568.6% compared to the reference system, as a result of recycling additional quantity of steel, aluminium and stainless steel scrap as well as disposing additional scarp to landfill. This came along with a marginal change in coal consumption i.e. 0.4 times of that of the reference system. Overall, for each resource type, quantities consumed by reference, retrofit and new-build power systems were of the same order of magnitude during dismantling and the end of life.

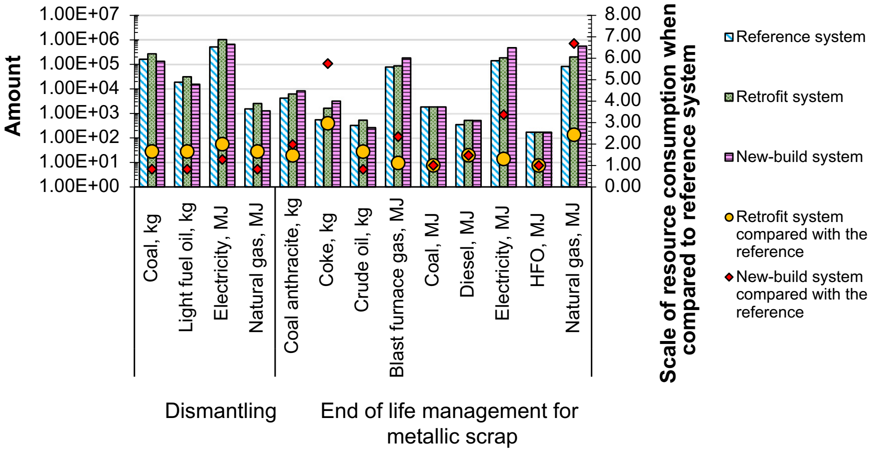

Fig. 6. Materials and fuel consumption of both retrofit and new-build systems when compared to those of the reference system during dismantling and end of life phases (in which a scale of 1 indicated no difference between the system being compared and the reference system whilst a scale of 7 suggested that the resource consumed by the retrofit or new-build system was 7 times of that of the reference system).

The quantity of resources consumed and emissions released by the power systems was mainly influenced by (i) mass of the components incorporated into the power systems for manufacture, dismantling and the end of life; and (ii) power demand and operational profile of components which were run to meet such demand (hereafter 'fuel consumers') during operation. The total mass of all components incorporated into the reference, retrofit and new-build systems was 549,960 kg, 644,420 kg and 915,619 kg respectively. The analysis showed that significant components of

(i) the reference system were diesel engines, auxiliary generators, propellers and shafts, which made up 92.66% of the total mass;
(ii) the retrofit system included diesel engines, auxiliary generators, propellers and shafts and batteries, which summed up to 85.88% of the total mass;
(iii) the new-build system consisted of diesel gensets, propulsion motors, thruster motors, propellers and shafts i.e. 74.93% of the total mass.

At LCI phase, correlations between resource consumption, emissions, fuel consumers, significant components and life cycle phases were observed: whilst significant components used up most of the resources during manufacture, dismantling and the end of life, fuel consumers were the primary cause of resource consumption and emissions during operation.

3.2. LCIA results

In relation to LCIA results, as illustrated in Fig. 7(a), all impact categories were found either of the same order or varied by 1 order of magnitude. However, the differences as per impact categories when compared to the reference system, showed a broad range from a significant reduction of 50.7% to a very pronounced increase of 422.2%, as illustrated in Fig. 7(b). Among all impact categories, the top two most pronounced increases were shown by the new-build system i.e. CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV), which were accounted for 391.3% and 422.2% respectively. This was because of the increased quantity of natural gas required for handling additional scrap, as reported in Section 3.1. The same impact categories caused by the retrofit system were, to a lesser extent, only 17.7% and 161.9% more burdensome than those attributable to the reference system. In relation to other impact categories, the retrofit system showed a decline ranging 2.7–6.6% in most impact categories at the expense of an increase of approximately 8% in CML2001: *Marine Aquatic Ecotoxicity Potential*, CML2001: *Freshwater Aquatic Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater* and Eco-Indicator99: *Ecosystem Quality – Ecotoxicity* (labelled as I, IV, XI and XXII respectively), 1–2% in CML2001: *Terrestric Ecotoxicity Potential* and ILCD: *Resource Depletion, Fossil and Mineral* (labelled as VIII and XX respectively). As such, as estimated per individual impact categories, the environmental impact attributable to the retrofit system was 0.93–1.18 times of that caused by the reference system, with the exception of Eco-Indicator99: *Resources – Fossil Fuels* (labelled as XXIV).

When the new-build system was compared to the reference system, most of the impact categories showed a reduction, to a greater extent, ranging between 35.7% and 50.7%, with the exception of 7 impact categories. A slight decline, i.e. 17.1%, was observed in Eco-Indicator99: *Ecosystem Quality – Land-Use* (labelled as XXV), whilst CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV)

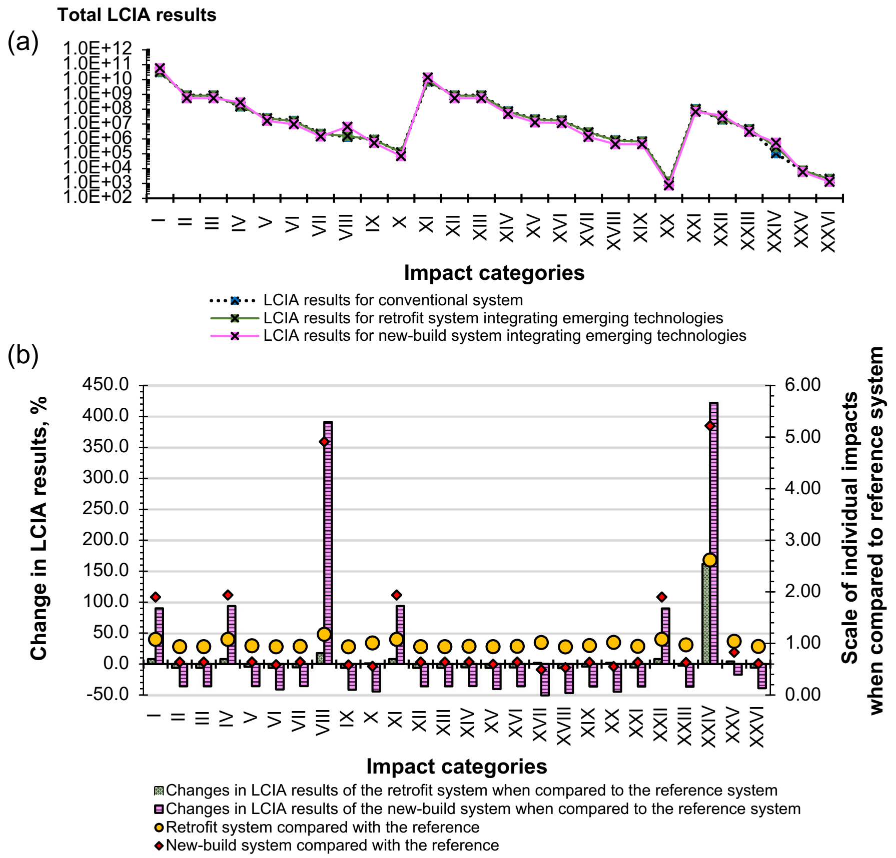

Fig. 7. Comparison of retrofit and new-build systems, in terms of (a) the magnitude of LCIA results; and (b) changes in LCIA results and the scale of the impact when compared to the reference system.

showed the two most pronounced increases among all impact categories, as reported earlier. The other four impact categories included CML2001: *Marine Aquatic Ecotoxicity Potential*, CML2001: *Freshwater Aquatic Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater* and Eco-Indicator99: *Ecosystem Quality – Ecotoxicity* (labelled as I, IV, XI and XXII respectively), which were 90.0–93.9% more burdensome than those of the reference system. Therefore, the environmental impact attributable to the new-build system was 0.49–1.94 times of that caused by the reference system for all impact categories assessed in the study, with the exception of CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV).

The analysis showed that CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV) were the two impact categories affected greatly by the implementation of retrofit and new-build systems, although *Marine Aquatic Ecotoxicity Potential*, *Ecotoxicity for Aquatic Freshwater* and *Ecosystem Quality – Acidification/Nutrification* were the most significant impact categories (in terms of magnitude) estimated by CML, ILCD and Eco-Indicator99 respectively. Overall, the findings led to comparative assertions: (i) despite more materials and energy were consumed during manufacture and the end of life, an overall improvement in environmental performance was achieved, as indicated by the reduction in the majority of the impact categories, to the detriment of a few; and (ii) between retrofit and new-build systems, the later showed the potential of greater abatement in most impact categories which also came along with a greater scale of burdens in one or two impact categories. As such, the environmental benefits brought by emerging technologies incorporated into an existing or a new-build power system as a whole were verified. The life cycle of the system must be appropriately managed with due care to avoid shifting the burdens from one impact to another while alleviating the environmental burdens at the same time.

3.3. Life cycle interpretation

3.3.1. Relative contribution

In identifying significant issues, contribution of significant components towards individual impact categories was analysed. It was found that LCIA results for most impact categories were largely caused by significant components, as illustrated in Fig. 8.

In the reference system, significant components (i.e. diesel engines, auxiliary generators, propellers and shafts which represented 92.66% of the total mass) were the primary causes of all impact categories, which resulted in approximately 91% of CML2001: *Marine Aquatic Ecotoxicity Potential*, CML2001: *Freshwater Aquatic Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater* and Eco-Indicator99: *Ecosystem Quality – Ecotoxicity* (labelled as I, IV, XI and XXII) and more than 97% for the others.

The total mass of the retrofit system was 1.17 times of that of the reference system. When emerging technologies were incorporated into retrofit system, contribution of significant components (i.e. diesel engines, auxiliary generators, propellers and shafts and batteries which made up 85.88% of the total mass) remained profound as they were attributable to approximately 84% of CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV) and 86.33–98.88% for the rest of the impact categories. In comparison with the reference system, contribution of these components dropped by

- approximately 15% in two particular impact categories i.e. CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV);
- approximately 4% in CML2001: *Marine Aquatic Ecotoxicity Potential*, CML2001: *Freshwater Aquatic Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater,* Eco-Indicator99: *Ecosystem Quality – Ecotoxicity* and Eco-Indicator99: *Ecosystem Quality – Land-Use* (labelled as I, IV, XI, XXII and XXV); and
- less than 2% for the remaining impact categories.

The new-build system had a total mass of 1.66 times of that of the reference system. Although the LCIA results of most impact categories attributable to the new-build system were of a lesser extent, as reported in Section 3.2, the influence of significant components in the new-build system (i.e. diesel gensets, propulsion motors, thruster motors and propellers and shafts which made up 74.93% of the total mass) were more prominent for most impact categories, which indicated an approximately 2% of increase in their contribution when compared to the significant components of the reference system. The significant components of the new-build system were attributable up to 99% of 18 impact categories. The other 8 impact categories which were of exception included

- CML2001: *Marine Aquatic Ecotoxicity Potential*, CML2001: *Freshwater Aquatic Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater* and Eco-Indicator99: *Ecosystem Quality – Ecotoxicity* (labelled as I, IV, XI and XXII), in which transformers connecting

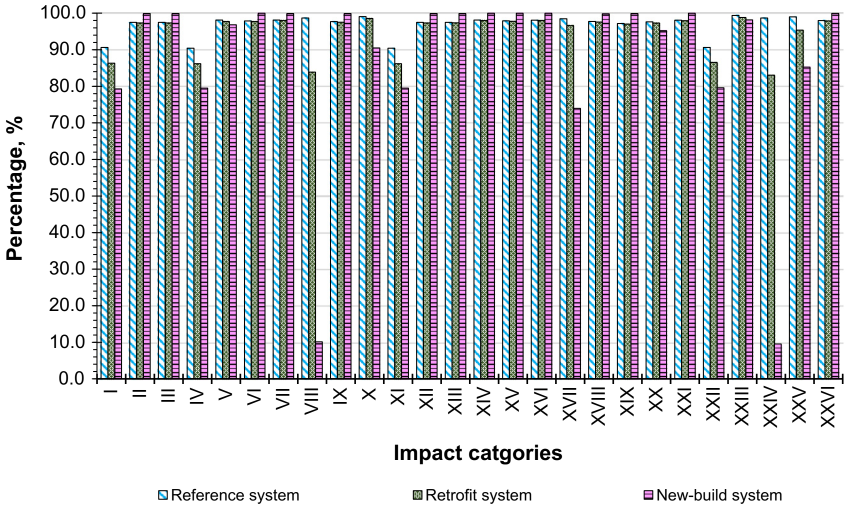

Fig. 8. Contribution of significant components, in%, towards LCIA results of individual impact categories for each power system.

propulsion drives were accounted for 6.27–6.42% whilst other components resulted in approximately 14% of these impact categories;

- Eco-Indicator99: *Ecosystem Quality – Land-Use* (labelled as XXV), in which PV and batteries systems resulted in approximately 5% each;
- ILCD: *Total Freshwater Consumption* (labelled as XVII), in which transformers connecting propulsion drives contributed approximately 10% whilst VFDs connecting propulsion and thruster motors respectively, batteries and thruster motors resulted in 2–3% of the impact each;
- CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV), in which transformers connecting propulsion and thruster drives, and those for distribution purpose at a power rate of 400 kW and 250 kW were the main sources i.e. approximately 63%, 10%, 4% and 7% respectively.

As such, it showed that the influence of significant components

- in both reference and retrofit systems (with a 17.2% of difference in the total mass) was in close proximity for most impact categories whilst components which constituted less than 5% of the total mass would have a negligible effect towards most impact categories and a mild consequence on impact categories relevant to (i) ecotoxicity potential in both reference and retrofit systems; and (ii) depletion of fossil for the retrofit system.
- in the new-build system was more dynamic when compared to the reference system (with a 66.5% of difference in the total mass), in which significant components had triggered a 2% increase in their contribution towards 18 impact categories (despite a reduction in most impact categories was observed) when compared to the significant components of the reference system whilst individual components, such as transformers, PV and battery systems which individually made up less than 5% of the total mass, had exerted a noticeable pressure on impact categories relevant to fossil fuel depletion, ecotoxicity potential, freshwater consumption and land use.

A closer look was taken at individual components as well as impact categories to compare critical processes of these power systems. The analysis indicated that the reference, retrofit and new-build systems were in agreement. Similar correlations were shown among critical processes, significance of individual components and impact categories, and nature of the impact categories assessed by CML2001, ILCD and Eco-Indicator99:

- disposing metallic waste of (i) diesel engines, auxiliary generators, propellers and shafts for both reference and retrofit systems; and (ii) diesel gensets, propulsion motors, thruster motors, propellers and shafts for the new-build system, was the principal contributors of the most significant impact categories which were relevant to ecotoxicity potential;
- operating (i) diesel engines and auxiliary generators for both reference and retrofit systems; and (ii) diesel gensets for the new-build system resulted in impact categories which were more moderate, i.e. those relevant to global warming, acidification, eutrophication, photochemical ozone creation and PM/respiratory inorganic health issues; and
- consuming resources during the process of manufacturing prime movers (i.e. (i) diesel engines for both reference and retrofit systems; and (ii) diesel gensets for the new-build system, and other less prominent components, i.e. (i) auxiliary generators, propellers and shafts for the reference and retrofit systems; and (ii) propellers and shafts, their connecting motors and transformers and/or thruster motors for the new-build system) led to impact categories which were of less significance i.e. those relevant to resource depletion.

Overall, despite a large quantity of resources i.e. energy and materials were involved during acquisition and manufacture, most environmental burdens of marine power systems occurred during operation and the end of life of the significant components, in particular diesel engines, auxiliary generators, diesel gensets, propulsion and thruster motors, propellers and shafts. Other technologies such as boilers, economisers, thrusters, VFDs, distribution transformers, battery systems, PV systems and cold ironing contributed to the environmental burdens to such an extent that they were not only relatively negligible when compared to the former components but also helped to reduce the environmental impact of the power systems when compared to the reference system over the same period of lifespan.

3.3.2. Sensitivity analysis on fuel consumption

In real-time operation, diesel engines, auxiliary generators and diesel gensets might be run without strictly following the optimal profile (which was modelled in the base case scenario for both retrofit and new-build systems) because of weather conditions, unexpected demand variation and unstructured business routine. As fuel consumption had been the primary concern of maritime stakeholders, scenario analysis was performed in this study with a focus on fuel consumption quantity to support sensitivity analysis. Additional scenarios were modelled to cover 10% less, 20% less, 10% more and 20% more fuel consumed by diesel engines and auxiliary generators for both reference and retrofit systems and diesel gensets for new-build system. The LCIA results for individual impact categories of both retrofit and new-build systems in each scenario were compared to those of the reference system in base case, 10% less fuel, 20% less fuel, 10% more fuel and 20% more fuel consumption scenarios one by one. The outcome of the analysis was illustrated in Figs. 9 and 10 respectively.

The analysis indicated that the impact attributional to the power systems varied with fuel consumed by diesel engines and auxiliary generators or diesel gensets very minimally, less pronouncedly or significantly, depending on the type of impact individually. For both systems, impact categories related to ecotoxicity and land use i.e. CML2001: *Marine Aquatic Ecotoxicity Potential*, CML2001: *Freshwater Aquatic Ecotoxicity Potential*, CML2001: *Terrestric Ecotoxicity Potential*, ILCD: *Ecotoxicity for Aquatic Freshwater,* Eco-Indicator99: *Ecosystem Quality – Ecotoxicity*, and Eco-Indicator99: *Ecosystem Quality – Land-Use* (labelled as I, IV, X–XI, XII and XV) were not responsive to changes in fuel consumption quantity. This was mainly because the impact was largely caused by other factors i.e. end-of-life management or storage.

On the other hand, the LCIA results for CML2001: *Abiotic Depletion of Fossil* and Eco-Indicator99: *Resources – Fossil Fuels* (labelled as VIII and XXIV) were more sensitive to changes in fuel consumption, if compared to other impact categories. This was justifiable as the impact was triggered by fuel consumption - variation in these LCIA results with changes in fuel consumption was previously perceived and verified in this sensitivity analysis. Taking a closer look, the two impact categories for retrofit system varied by 0.95–1.50 when the LCIA results were compared to those of the reference system at different fuel consumption scenarios. In this matter, the new-build system was found far more sensitive which indicated a range of 4.81–5.01 for CML2001: *Abiotic Depletion of Fossil* (labelled as VIII) and 5.12–5.32 for Eco-Indicator99: *Resources – Fossil Fuels* (labelled as XXIV) when compared to the reference ship, although diesel gensets of the new-build system consumed less fuel than diesel engines and auxiliary generators of the retrofit

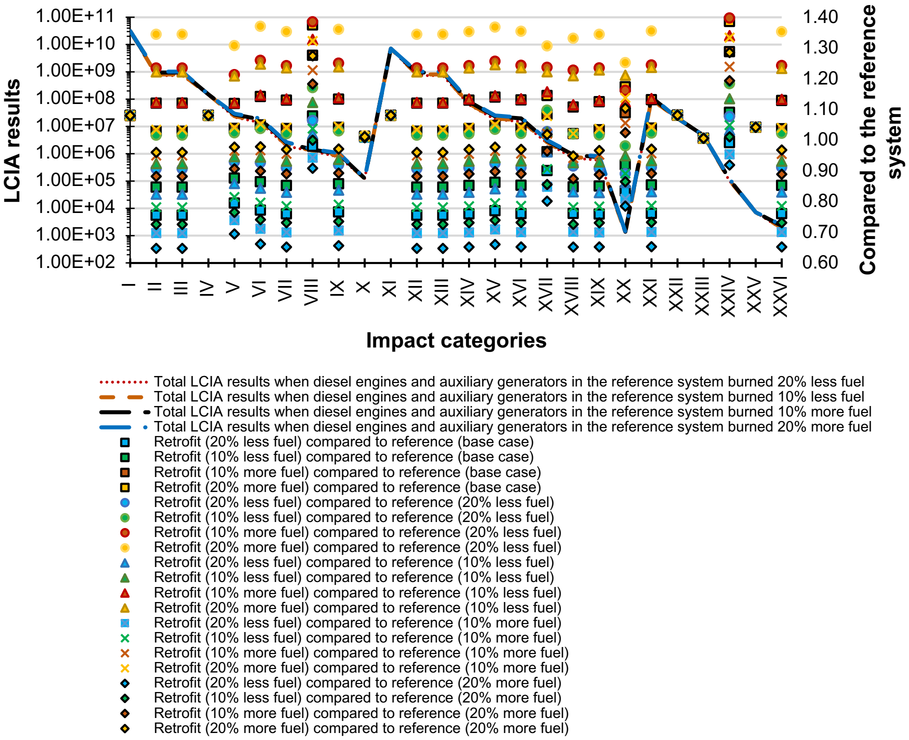

Fig. 9. Changes in LCIA results of the retrofit system compared to reference system at various fuel consumption quantity scenarios.

system during operation. It was important to point out that these impact categories were still of the same order of magnitude, albeit the LCIA results of the new-build system were 4.81–5.32 times of those of the reference system. The analysis indicated that fuel consumption during other life cycle phases for the new-build system seemed to exert a stronger influence. The trend was in agreement with the total mass of the systems in which the new-build system was relatively more complex (involving more components) and consequently acquired more resources throughout the lifespan, which resulted in heavier burdens in these particular impact categories.

For the LCIA results of other impact categories at different fuel consumption scenarios, new-build, retrofit and reference systems, overall, showed the lowest, moderate and highest magnitude respectively, where all systems had the least impact when most fuel was saved (i.e. 20% of saving in this sensitivity analysis). It was important to note that fuel consumed by the reference system was a decisive factor in this sensitivity analysis - a smaller difference would be shown if more fuel was burned by the reference system. Although the figures were subject to the quantity of fuel consumed by the systems, the LCIA results for the retrofit and new-build systems were 0.65–1.37 and 0.34–0.92 times of those of the reference system, respectively when fuel consumption varied by ±10% and ±20%. Altogether, sensitivity analysis showed that results presented in this study were reliable (by showing small range of changes in comparing most impact categories to those of the reference system) and consistent (by showing similar trends for impact categories of the same kind).

3.3.3. Closing remarks

The LCI results showed that both retrofit and new-build systems, when compared to a conventional system, would require more resources during manufacture and the end of life whilst burning less fuel and releasing less emissions during operation, which resulted in a reduction (reasonably by the retrofit system and more significantly by the new-build system) in most impact categories at the expense of a few. The magnitude of the LCI and LCIA results presented here was subject to input data, assumptions and limitations of the study. Substituting new data of higher quality which addressed spatial and temporal dimensions for current input data, varying any assumptions and addressing any limitations of the study would change the magnitude of the LCI and LCIA results. Without in-depth investigation, no conclusive remark could be drawn whether such change would have a negligible, mild, moderate or strong influence over the LCIA results. It was believed that the trends of the key findings (as presented in this article in relation to (i) the correlations between resources consumption, emissions, fuel consumers, significant components and life cycle phases which was identified from LCI results; (ii) the environmental benefits of the retrofit system and the potential of greater abatement that was enabled by the new-build all-electric power system; (iii) the influence of significant components and critical processes; and (iv) the influence of fuel consumption quantity on individual impact categories) would remain valid, unless proven otherwise when the study was repeated with newer and higher quality data, despite changes in the LCI and LCIA results. This was because the massive scope of the studies and the complex nature of the power systems (in which the technical work involved energy generation, conversion, storage, distribution, utilisation and management) would likely to counteract the influence of the input data, assumptions and limitations – a conjecture stimulated from this study.

3.3.4. Future work/outlook

To extend existing knowledge on the environmental performance of marine power systems, a range of LCA studies covering various aspects could be carried out in future. The study could be repeated if newer data were available to dispel any assumptions made in this comparative study and overcome any current limitations (as reported in Section 2). The outcome would be useful to verify the conjecture presented in Section 3.3.3 i.e. the influence of input data, assumptions and limitations would likely to be counteracted by the complex nature of power systems and the

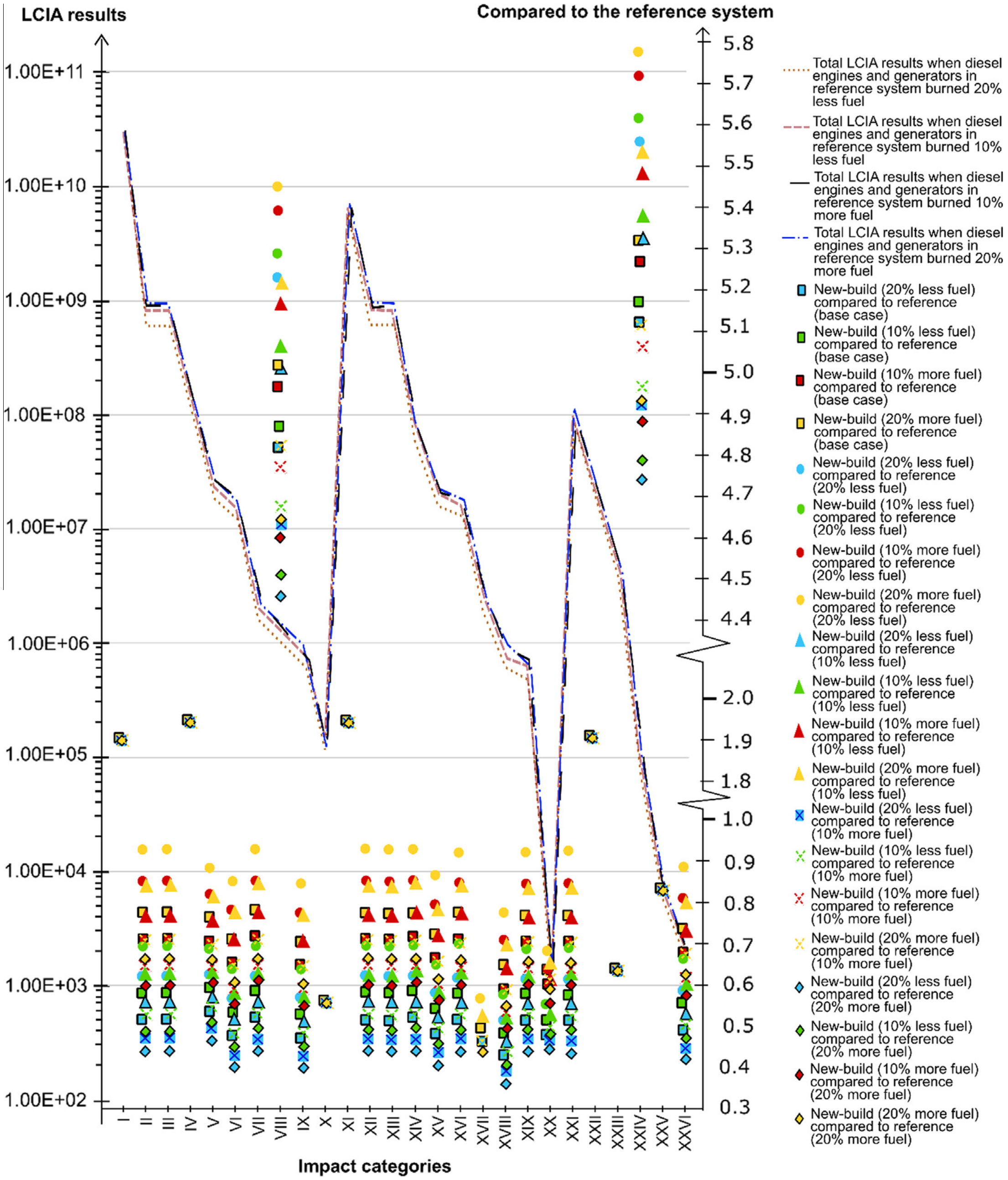

Fig. 10. Changes in LCIA results of the new-build system compared to reference system at various fuel consumption quantity scenarios.

massive scope of the study. The power systems assessed in this comparative study were proposed for intra-European RoRo cargo ships transiting within ECAs. In practice, cargo ships could engage with alternative routes (i.e. outside ECAs) and business services (e.g. tramp trade, short sea or deep sea shipping). Indeed, the same power systems were applicable to other ship types such as tankers, bunkers, container and general cargo ships. To verify whether or not the environmental impact of marine power systems would vary significantly with business routes, services and ship types, future LCA case studies should explore alternative ship types following the same or divergent business routes and/or services. In addition, alternative power system designs which integrated other advanced technologies such as waste heat recovery and fuel cells could be investigated. Also, case studies could be carried out to apply alternative characterisation models (such as ReCiPe and IMPACT2006+). Provided characterisation models for thermal pollution, noise disturbance and odour were incorporated into the software in the future, the impact should be evaluated. To support uncertainty analysis, the software could be equipped with advanced methodologies e.g. stochastic modelling, non-parametric good-of-fit test, analytical method, fuzzy number, Bayesian and interval calculation. In relation to sensitivity analysis, the software could incorporate advanced statistics such as variance, sum of squared errors, polynomial models and sensitivity indices. The scope of the study could be broadened by performing economic and risk assessments on the power systems, as the benefits of implementing an advanced system would always come along with financial burdens and risks.

4. Conclusions

It was argued that existing knowledge could not determine the superiority of power systems that integrating innovative technologies from an environmental perspectives. To bridge such knowledge gap, this article presented a comparative LCA study which compared retrofit and new-build systems to a conventional system to verify their environmental benefits based on a bottom-up integrated system approach. The results estimated from LCA models allowed for a comparison of the systems in terms of materials and energy consumption, emissions, critical processes and significant components, leading to the identification of correlations among these parameters. The comparison in terms of environmental impact as per individual impact categories verified the huge mitigation potential of the new-build all-electric system in most impact categories compared to the retrofit and reference systems. The results were further interpreted in terms of relative contribution of significant components and critical processes, followed by a sensitivity analysis on the influence of fuel consumption quantity on the estimated impact. The environmental benefits brought by incorporating emerging technologies into marine power systems were verified based on a whole-system perspective. Appropriate management throughout the life cycle was warrant to avoid shifting the burdens from one impact category to another while alleviating the environmental burdens at the same time. The study was important as the findings had provided insights to maritime stakeholders, in particular regulators, ship owners and operators, and assisted in their long-term organisational decision making, in addition to advancing existing understanding of the environmental performance of marine power systems as well as stimulating new conjecture for future work. Also, future research should extend to adopt newer data (covering spatial and temporal factors), substitute more data for assumptions made in this study, address limitations, cover diverse operational profiles for other sailing routes and services, employ similar power systems onboard other ship types, investigate alternative power system designs, apply alternative characterisation models, assess thermal pollution, noise disturbance and odour, apply advanced methodologies for uncertainty and sensitivity analyses, and perform economic and risk assessments.

Acknowledgements

The work presented in this article was disseminated for two research projects: (i) INOvative Energy MANagement System for Cargo SHIP (INOMANS^{2}HIP funded by European Commission, grant agreement no: 266082) and (ii) Sustainable Thermal Energy Management Network (SusTEM, funded by the Research Councils UK Energy Programme, Reference: EP/K039377/1). Gratitude was extended to all parties and research partners that provided data required for the work, in particular Netherlands Organisation for Applied Scientific Research (TNO), Offshore Renewable Energy Catapult (NAREC), Wärtsilä Netherlands BV, Imtech Marine Netherlands BV and the ship owner. 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.

References

[1] Barki D, Rogers J, editors. United Nations conference on trade and development (UNCTAD). New York and Geneva; 2015. p. 1–122. [Review of maritime transport].
[2] Third IMO GHG study; 2014. Available from: <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Greenhouse-Gas-Studies-2014.aspx> [cited 2016, 4 February].
[3] Winiwarter W et al. Quality considerations of European PM emission inventories. Atmos Environ 2009;43(25):3819–28.
[4] Tse LKC et al. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. J Power Sources 2011;196(6):3149–62.
[5] International Convention for the Prevention of Pollution from Ships (MARPOL); 2011 Available from: <http://www.imo.org/About/Conventions/ListOf Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx> [cited 2012, 5 March].
[6] Chang D et al. A study on availability and safety of new propulsion systems for LNG carriers. Reliab Eng Syst Saf 2008;93(12):1877–85.
[7] Veneri O et al. Overview of electric propulsion and generation architectures for naval applications. In: Electrical systems for aircraft, railway and ship propulsion (ESARS), 2012. IEEE; 2012.
[8] Zahedi B, Norum LE, Ludvigsen KB. Optimized efficiency of all-electric ships by dc hybrid power systems. J Power Sources 2014;255:341–54.
[9] Schmitt K. Modeling and simulation of an all electric ship in random seas. Massachusetts Institute of Technology; 2010.
[10] Apsley JM et al. Propulsion drive models for full electric marine propulsion systems. IEEE Trans Ind Appl 2009;45(2):676–84.
[11] Staunton-Lambert Mark J. Significant ships of 2010 – a publication of The Royal Institution of Naval Architects; 2010.
[12] Winnes H, Fridell E. Emissions of NOx and particles from manoeuvring ships. Transport Res D - Transp Environ 2010;15(4):204–11.
[13] Walsh C, Bows A. Size matters: exploring the importance of vessel characteristics to inform estimates of shipping emissions. Appl Energy 2012;98:128–37.
[14] Ushakov S et al. Emission characteristics of GTL fuel as an alternative to conventional marine gas oil. Transport Res D - Transp Environ 2013;18:31–8.
[15] Yang ZL et al. Selection of techniques for reducing shipping NOx and SOx emissions. Transport Res D - Transp Environ 2012;17(6):478–86.
[16] Moreno-Gutiérrez J et al. Methodologies for estimating shipping emissions and energy consumption: a comparative analysis of current methods. Energy 2015;86:603–16.
[17] Duran V, Uriondo Z, Moreno-Gutiérrez J. The impact of marine engine operation and maintenance on emissions. Transport Res D - Transp Environ 2012;17(1):54–60.
[18] Vanesa Durán Grados C et al. Correcting injection pressure maladjustments to reduce NOX emissions by marine diesel engines. Transport Res D - Transp Environ 2009;14(1):61–6.
[19] Uriondo Z et al. Effects of charged air temperature and pressure on NOx emissions of marine medium speed engines. Transport Res D - Transp Environ 2011;16(4):288–95.
[20] Fagerholt K, Psaraftis HN. On two speed optimisation problems for ships that sail in and out of emission control areas. Transport Res D - Transp Environ 2015;39:56–64.
[21] Psaraftis HN, Kontovas CA. Speed models for energy-efficient maritime transportation: a taxonomy and survey. Transport Res C - Emerg 2013;26:331–51.
[22] Johnson H, Styhre L. Increased energy efficiency in short sea shipping through decreased time in port. Transport Res A - Policy Pract 2015;71: 167–78.
[23] Schøyen H, Bråthen S. Measuring and improving operational energy efficiency in short sea container shipping. RTBM 2015;17:26–35.
[24] 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.
[25] Welaya Y, El Gohary MM, Ammar NR. A comparison between fuel cells and other alternatives for marine electric power generation. Int J Nav Arch Ocean 2011;3(2):141–9.
[26] Kobougias I, Tatakis E, Prousalidis J. PV systems installed in marine vessels: technologies and specifications. Adv Power Electron 2013;2013.
[27] Li Q et al. A study on the performance of cascade hard sails and sail-equipped vessels. Ocean Eng 2015;98:23–31.
[28] Traut M et al. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Appl Energy 2014;113:362–72.
[29] 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.
[30] Sciberras EA, Zahawi B, Atkinson DJ. Electrical characteristics of cold ironing energy supply for berthed ships. Transport Res D - Transp Environ 2015;39:31–43.
[31] Dedes EK, Hudson DA, Turnock SR. Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping. Energy Pol 2012;40:204–18.
[32] 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.
[33] 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.
[34] Romero Gómez J 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.
[35] Jafarzadeh S, Utne IB. A framework to bridge the energy efficiency gap in shipping. Energy 2014;69:603–12.
[36] Ölçer A, Ballini F. The development of a decision making framework for evaluating the trade-off solutions of cleaner seaborne transportation. Transport Res D - Transp Environ 2015;37:150–70.
[37] Kim H-J et al. An epsilon-optimal algorithm considering greenhouse gas emissions for the management of a ship's bunker fuel. Transport Res D - Transp Environ 2012;17(2):97–103.

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

[39] Environmental management – life cycle impact assessment – principles and framework. British Standard; 2006.

[40] Environmental management – life cycle impact assessment – requirements and guidelines. International Organisation for Standardisation (ISO); 2006.

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

[42] 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.

[43] Kameyama M, Hiraoka K, Tauchi H. Study on life cycle impact assessment for ships. Japan: NMRI; 2007.

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

[45] Basurko OC, Mesbahi E. Methodology for the sustainability assessment of marine technologies. J Clean Prod 2014;68:155–64.

[46] 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.

[47] Fet AM. Environmental reporting in marine transport based on LCA. Proc IMarEST J Marine Design Oper 2002:1476–556.

[48] 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.

[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. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proc Inst Mech Eng M - J Eng 2011;225(M2):97–110.

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

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

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

[54] 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.

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

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

[57] Ling-Chin J, Roskilly AP. 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. Energy Convers Manage 2016;117:305–18.

[58] Ling-Chin J, Roskilly AP. 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. Appl Energy 2016;181:416–34.

[59] Chatzinikolaou SD, Ventikos NP. Holistic framework for studying ship air emissions in a life cycle perspective. Ocean Eng 2015;110(Part B):113–22.

[60] 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.

[61] 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); 2002.

[62] Yellishetty M et al. Environmental life-cycle comparisons of steel production and recycling: sustainability issues, problems and prospects. Environ Sci Policy 2011;14(6):650–63.

[63] Norgate TE. Metal recycling: an assessment using life cycle energy consumption as a sustainability indicator. Minerals; 2004 [Editor].

[64] Kaplan RS, Ness H. Recycling of metals. Conserv Recycl 1987;10(1):1–13.

[65] Moats M et al. Recycling of nickel, cobalt and platinum-group metals, in Extractive metallurgy of nickel, cobalt and platinum group metals. Elsevier; 2011.

[66] Gaustad G, Olivetti E, Kirchain R. Improving aluminum recycling: a survey of sorting and impurity removal technologies. Resour Conserv Recycl 2012;58:79–87.

[67] Paraskevas D et al. Environmental modelling of aluminium recycling: a life cycle assessment tool for sustainable metal management. J Clean Prod 2015;105:357–70.

[68] Muchova L, Eder P, Villanueva A. End-of-waste criteria for copper and copper alloy scrap. Spain: European Commission; 2011.

[69] Trozzi C, et al. EMEP/EEA air pollutant emission inventory guidebook 2013: technical guidance to prepare national emission inventories. Luxembourg; 2013.

[70] Genaidy AM et al. Evidence-based integrated environmental solutions for secondary lead smelters: pollution prevention and waste minimization technologies and practices. Sci Total Environ 2009;407(10):3239–68.

[71] Reck BK et al. Anthropogenic nickel cycle: insights into use, trade, and recycling. Environ Sci Technol 2008;42(9):3394–400.

[72] Gordon RB et al. The characterization of technological zinc cycles. Resour Conserv Recycl 2003;39(2):107–35.

[73] Bare JC, Gloria TP. Critical analysis of the mathematical relationships and comprehensiveness of life cycle impact assessment approaches. Environ Sci Technol 2006;40(4):1104–13.

[74] Goedkoop M, et al. ReCiPe 2008 – a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. The Nerthelands; 2009. p. 126.

[75] Chan YT, Tan RBH, Khoo HH. Characterisation framework development for the SIMPASS (Singapore impact assessment) methodology. Int J Life Cycle Assess 2012;17(1):89–95.

[76] ILCD handbook: framework and requirements for life cycle impact assessment models and indicators. Luxembourg; 2010.

[77] Guinée JB et al. Life cycle assessment: an operational guide to the ISO standards—Part 3. Scientific background. The Netherlands: Centre of Environmental Science (CML); 2001.

[78] Goedkoop M, Spriensma R. The eco-indicator99: a damage oriented method for life cycle impact assessment: methodology report Available from:Available from: <http://www.teclim.ufba.br/jsf/indicadores/holan%20ecoindicator%2099.pdf>2001 [Cited 2016, 27 July].

[79] Baitz M, et al. GaBi database and modelling principles 2014. Germany; 2014. p. 1–178. Available from: <https://issuu.com/peinternational/docs/gabi_modelling_principles_2014> [Cited 2016, 27 July].

[80] Martínez E et al. Comparative evaluation of life cycle impact assessment software tools through a wind turbine case study. Renew Energy 2015;74:237–46.