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A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability

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ABSTRACT

The shipping industry has been facing great pressure to become more sustainable, emanating from the increasingly stringent environmental regulations, fuel prices volatility and societal needs. As a result, a variety of technologies have been developed aiming to improve the environmental and economic performance of the modern ship energy systems, however leading to additional challenges for the technology selection during the design process. This study introduces an innovative method that integrates the economic and environmental aspects of sustainability to support decisions on the synthesis of the modern ship energy systems. The method includes a simulation model for predicting the energy systems performance during the ship lifetime. The genetic algorithm NSGA-II, is employed to solve the multi-objective combinatorial optimisation problem of selecting the integrated ship energy systems configuration. The derived results are visualised to reveal the Pareto front and the trade-offs among the objectives. The method is novel in supporting the synthesis of the integrated ship energy systems, as it includes both environmental and economic objectives, as well as evaluates the performance of the systems over an expected operational profile. The developed method is implemented for the case study of an Aframax oil tanker and the derived results analysis indicates that the ship energy systems sustainability can be improved by adopting LNG fuel and dual fuel engines technology, as well as by introducing other emerging technologies like fuel cells and carbon capture, although the latter is associated with a high cost. It is concluded that the inclusion of both environmental and economic objectives highlights the trade-offs between more environmentally friendly or cost efficient configurations, thus supporting the multi-objective decision-making process.

1. Introduction

In the past few years, there has been a growing interest to enhance the sustainability of shipping operations. Shipping has a very important role in the global economy, with 90% of the global trade being transported by ships [1]. Although ship transportation is considered one of the most environmentally friendly modes of transport [2], great attention has been placed on improving the environmental sustainability due to the magnitude of the shipping operations [3,4]. Global shipping accounts for approximately 3% of global CO_2 emissions [5] and in the case where international shipping was a country it would be ranked the sixth carbon emissions producer [6]. With regard to other anthropogenic emissions, 4–9% of global SOx and 15% of NOx emissions are attributed to shipping operations [7] and their further increase of around 40–50% is anticipated from 2000 to 2020 [8]. Finally, shipping operations have a major impact on the fossil fuel depletion as more than 350 million tonnes of fossil fuels per year are consumed [9], corresponding to 5% of the total transportation sector energy consumption [10].

Due to the significant environmental impact of the shipping operations, the environmental regulations imposed in the shipping industry by the International Maritime Organisation (IMO) as well as national authorities have become more stringent. Regulations have been implemented to set limits on the emissions of NOx and SOx from ship engines and the intention is to become even stricter in the future [11]. IMO introduced the first maritime energy efficiency regulation in 2011 [11], which is highly related to the reduction of the CO_2 gas emissions. According to this regulation, all new vessels have to comply with the Energy Efficiency Design Index (EEDI) [12] and all new and existing ships need to have a specific Ship Energy Efficiency Management Plan (SEEMP) [13]. However, these measures could not manage to reach the global targets set for CO_2 emissions [14]. In consequence, a Monitoring, Reporting and Verification (MRV) system for carbon dioxide emissions was introduced by the EU [15]. Furthermore, it is

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Nomenclature

Abbreviations

CAPEX	capital expenditure (€)
CC	carbon capture system
CO_2	carbon dioxide
D	diesel engine
DF	dual fuel engine
DFG	dual fuel generator
DG	diesel generator
ECA	emission control area
EGR	exhaust gas recirculation
EU ETS	European emissions trading scheme
FC	fuel cells
HFO	heavy fuel oil
IMO	International Maritime Organisation
LCC	life cycle cost (€)
LHV	lower heating value of fuel (kJ/kg)
LNG	liquefied natural gas
LSHFO	low sulphur heavy fuel oil
MCR	maximum continuous rating
MDO	marine diesel oil
MGO	marine gas oil
NG	natural gas
NOx	nitrogen oxides
O&M	operational and maintenance
OPEX	operational expenditure (€)
SCR	selective catalytic reactor
SG	shaft generator
SOx	sulphur oxides
WHR	waste heat recovery

Parameters

df	deterioration factor of the engine (%)
C_c	capital cost factor (€/kW)
C_{con}	consumables cost factor (€)
cf	correction factor from ISO conditions
C_f	fuel cost factor (€/t)
C_m	maintenance cost factor (€/kWh)
Δh	specific enthalpy difference from feedwater to saturated steam (kJ/kg)
E	annual emissions (g)
EF_{eb}	emission factor energy based (g/kWh)
EF_{fb}	emission factor fuel consumption based (g/g of fuel)
ega	exhaust gas amount (kg/s)
egt	exhaust gas temperature (°C)
h	time per operational phase (hours/year)
i	operational phases i = 1…I
ir	interest rate (%)
L	load (–)
$\dot{m}_s$	saturated steam mass flow (kg/h)
$\dot{m}_f$	fuel amount mass flow (kg/h)
NP	number of pollutants
O	alternative technological solutions
p	pollutant
P	power (kW)
P_n	nominal power (kW)
rpm	revolutions per minute (r/min)
sfc	specific fuel consumption (g/kWh)
sgc	specific gas consumption (g/kWh)
$spoc$	specific pilot oil consumption (g/kWh)
t_y	set of emission reduction technologies, y = 1…O_{er}
t_z	set of energy efficiency technologies, z = 1…O_{ee}
Y	lifetime operation (years)

Greek symbol

η_{th}	thermal boiler efficiency

Subscripts

ae	auxiliary engine
ed	electric demand
ep	electric power
me	main engine
mpr	minimum power requirements
p	pollutant
pd	propulsion power demand
pp	propulsion power
ss	sub-system
td	thermal demand
th	thermal boiler
tp	thermal power

Independent decision variables

$b_{p,y}$	the binary variable that equals 1 if the emission reduction technology is selected and 0 if it is not
b_z	the binary variable that equals 1 if the energy efficiency technology is selected and 0 if it is not
ee	the vector that includes decision variables for the energy efficiency sub-system
er	the vector that includes decision variables for the emission reduction sub-system
es	the vector that includes decision variables for the electric sub-system
N	the discrete variable for the number of sets
$P_{n,me}$	the discrete variable for the nominal power of the main engine
ps	the vector that includes decision variables for the propulsion sub-system
ts	the vector that includes decision variables for the thermal sub-system

Decision variables sets

f_{ae}	the set of fuel type alternatives for auxiliary engine {1…O_{fae}}
f_{me}	the set of fuel type alternatives for main engine {1…O_{fme}}
f_{th}	the set of fuel type alternatives for thermal boiler {1…O_{fth}}
t_{ae}	the set of auxiliary electric alternative types {1…O_{ae}}
t_{me}	the set of main engine alternative types {1…O_{me}}
t_{th}	the set of thermal boiler alternative types {1…O_{th}}

discussed to introduce shipping operations into the European Emission Trading Market Scheme (EU ETS) for CO_2 emissions as well as to tax the carbon emissions [16], in a manner similar to land-based power plants. As a result of this changing regulatory landscape, in order to achieve compliance with the existing and future regulations, ship-owners will be necessitated to retrofit their ship energy systems with emission reduction technologies, to use more expensive low-sulphur fuel, or to employ waste heat recovery technologies, thus increasing the shipping expenses.

Therefore, the shipping industry is required to pursue more