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Techno economic and environmental assessment of Flettner rotors for marine propulsion

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ABSTRACT

Wind energy is a mature renewable energy source that offers significant potential for near-term (2020) and long-term (2050) greenhouse gas (GHG) emissions reductions. Similar to all sectors of the transportation industry, the marine industry is also focused towards reduction of environmental emissions. A direct consequence of this being is a renewed interest in utilising wind as supplementary energy source for propulsion on cargo/merchant ships.

This research utilises a techno economic and environmental analysis approach to assess the possibility and benefits of harnessing wind energy, with an aim to establish the potential role of wind energy in reducing GHG emissions during conventional operation of marine vessels. The employed approach enables consistent assessment of different competing traditional propulsion systems when operated in conjunction with a novel environmental friendly technology, in this instance being the Flettner rotor technology. The assessment specifically focuses on quantifying the potential and relative reduction in fuel consumption and pollutant emissions that may be accrued while operating on typical Sea Lines of Communication.

The results obtained indicate that the implementation of Flettner towers on commercial vessels could result in potential savings of up to 20% in terms of fuel consumption, and similar reductions in environmental emissions.

1. Introduction

International trade depends significantly on international shipping. It is estimated that around 90% of international cargo are carried on ships (International Chamber of Shipping, 2014). This is due to the low costs and the high reliability of this mode of transportation.

The sustainability of the shipping industry is directly linked to the demand and the effective remuneration obtained through the minimization of the operating costs. Currently, marine fuel price is one of the major factors affecting the overall operating costs of the shipping industry, but with the stricter regulations on pollutant emissions set by the International Maritime Organization and the possible introduction of emission taxation, this trend is set to change. The Marine Pollution (MARPOL) annex VI (Marine Environment Protection Committee, 2011) has set strict limits on NOx, SOx and CO_2 emissions. Furthermore, the likely introduction of carbon emission taxation in the future has resulted in driving research in the marine industry towards sourcing environmentally optimised solutions.

It is evident that the principal source of environmental emissions from an operational ship is from the exhaust gases of the ship's propulsion systems. Investigating the causes and the methods to reduce pollutant emission from a marine vessel's propulsion systems is therefore of paramount importance. Consequently, a significant number of research studies have been undertaken on environmentally sustainable marine propulsion solutions in recent years. The problem has been tackled from different perspectives, and therefore, it has been driven towards investigating the effects of the introduction of new propulsion technologies and the utilisation of cleaner fuels.

Marine propulsion power plants are mainly internal combustion engines with a majority of commercial vessels being powered by diesel engines (El-Gohary, 2013). Gas turbine power plants as propulsion systems have also been used on ships, however owing to favourable high power to weight ratios their exploitation has primarily been prevalent in the high speed ferries sector and military applications, due to the high speed requirements.

However, given the current and compelling debate on improved environmental solutions, combined with the increased efficiency and the high compatibility with natural gas, the conventional gas turbine is now being increasingly considered for commercial exploitation. An important overview on future marine propulsion technologies has been presented

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Nomenclature

A	Flettner tower area [m^2]
c	Width of normal distribution
C_D	Drag coefficient
C_L	Lift coefficient
C_{mc}	Moment Coefficient
d_T	Cylinder diameter [m]
g	Gravity acceleration [m/s^2]
IMO	International Maritime Organization
L	Waterline length [m]
LNG	Liquid natural gas
L_T	Cylinder length [m]
MARPOL	Marine pollution
MDO	Marine Diesel Oil
O&M	Operation and Maintenance
p	Pressure [Pa]
P_{req}	Power required to rotate the tower [W]
R_{AW}	Waves added resistance [N]
$R_{AW\ p}$	Dimensionless peak resistance value
Re_{Ω}	Rotational Reynolds
TERA	Techno-economic Environmental Risk Analysis
T_q	Tower frictional moment [N-m]
v	Velocity [m/s]
V	Velocity of the vessel [knots]/[m/s]
$V\varepsilon$	Apparent Wind Velocity [m/s]
β	Angle between the vessel bow and the real wind direction [°]
ε	Apparent wind angle [°]
μ_T	Flow dynamic viscosity [Pa-s]
ρ	Density [kg/m^3]
ω	Frequency
ω'	Frequency for half peak value
ω_p	Peak frequency
Ω_T	Cylinder rotational speed [rad/s]
Emissions	
CO_2	Carbon Dioxide
NOx	Nitrogen oxide
SOx	Sulphur oxide
Finance	
$	Dollars
$/kWh	Dollars per kilowatt-hour
$/l	Dollars per liter
$/mmBTU	Dollars per million British thermal unit
$/tons	Dollars per tonne
AC	Actualised costs
$Costs_j$	Costs at year j
i	Discount Rate
j	Year number
n	Total number of years

by Parker (2013). His research defines various technologies solutions, which include nuclear propulsion, batteries, fuel cells, superconducting electric motors, renewable energies, Organic Rankine Cycle and hybrid propulsion. These technologies, he proposes, will be necessary in order to overcome the impact of fossil fuel consumption and the related environmental issues. For existing ships, the foremost prospect is to install exhaust gas attenuation technologies or to utilize fuels that produce lower pollutant emissions. As a short to medium goal, the scenario is to continue the development of cleaner fuel infrastructure as well as wide scale introduction and application of hybrid propulsion systems. The medium to long term target is to include alternative fuel options such as fuel cells, electrical batteries and also possibly nuclear power. A detailed assessment of the application of nuclear energy for merchant marine propulsion has been developed (Hirdaris et al., 2014). Another key technology, where a waste heat recovery system is combined with a conventional power plant, which is already well established for land based application, is now also being assessed for marine propulsion (Burel et al., 2013; Livanos et al., 2014).

It is therefore opined that key methods to reduce pollutant emissions are centred on the application of novel technologies. These range from application of cleaner fuels, technologies aimed at exploitation of renewable sources of energy and nuclear propulsion. Studies indicated in references (Alfonsín et al. (2014) and Andrews and Shabani (2012)) have also highlighted the employment of Hydrogen as a feasible alternative for a sustainable propulsion system. Other possible fuels that have been assessed in the past include liquefied natural gas (LNG) and various biofuels (Brynolf et al., 2014).

Application of renewable energy sources in the context of emission reduction is a very promising solution and hence it is actively being researched in the marine propulsion sector. There are various interesting research studies that have been undertaken on wind assisted propulsion systems in the past. Some of the key studies include those undertaken by Leloup et al. (2014) and Leloup et al. (2016). The work was focused on kite propulsion and considered an analytical method to assess fuel savings. Traut et al. (2014) developed a comparative analysis on kite and Flettner rotor technologies to assess the potential of these technologies in reducing fuel consumption. Bergeson (Bergeson et al., 1985); Rojon and Dieperink (2014) have, in their works, categorised various drawbacks and advantages of propulsion technologies harnessing wind power.

There have also previously been interesting studies undertaken on sail assisted ships (Shukla and Kunal, 2009; Lambrecht et al., 1994), on horizontal-axis wind turbines (Bockmann and Steen, 2011) kites and Flettner rotor technologies (Traut et al., 2014) for marine propulsion. A novel methodology for assessing the proper design of ships with wind-assisted propulsion has been presented by Viola et al. (2015).

However after an extensive literature review it has been established that there exists a literature gap in the full investigation of the application and potential of utilisation of Flettner rotor technology for marine propulsion. The aim of this work is therefore to demonstrate its application in combination with a conventional propulsion system through the application of TERA (Techno economic and Environmental Risk Assessment) methodology and to assess its potential as a possible novel environmental solution.

Talluri et al. (2016) have presented the utilisation of a similar techno economic approach and framework previously in the context of Vertical Axis Wind Turbine (VAWT). The work aimed to demonstrate the consistent assessment potential of the method in the context of the VAWT and its application in conjunction with other propulsion technologies.

Prior explaining the methodology applied, as this research is focused on the implementation of Flettner towers on commercial vessels as an alternative mean of propulsion, the maritime application and the working principles of this technology will be described in detail in the following section.

1.1. Flettner rotor

The Flettner rotor technology is an innovative technology created by Anton Flettner, who applied for a patent on the concept in 1922. Flettner, with the aid of Betz, Ackeret and Prandtl, applied this concept to a marine vessel and created the first wind-powered ship called "Buckau", which utilised the Flettner towers as the primary source of propulsive power. However, due to inadequacies in overall operational performance and