Ocean Engineering 121 (2016) 301–311

Contents lists available at ScienceDirect

Ocean Engineering

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

Techno economic and environmental assessment of wind assisted marine propulsion systems

L. Talluri [a,*], D.K. Nalianda [b], K.G. Kyprianidis [c], T. Nikolaidis [b], P. Pilidis [b]

[a] Department of Industrial Engineering, University of Florence, Viale Morgagni 40-44, Florence 50134, Italy
[b] Propulsion Engineering Centre, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, Bedfordshire MK43 0AL, United Kingdom
[c] Future Energy Centre, Department of Energy, Building and Environment, School of Business, Society and Engineering, Mälardalen University, Box 883, Högskoleplan 1, 721 23 Västerås, Sweden

ARTICLE INFO

Article history:
Received 7 October 2015
Received in revised form
7 April 2016
Accepted 30 May 2016

Keywords:
Gas turbine
Diesel engine
Vertical axis wind turbine
Fuel consumption
Pollutant emissions

ABSTRACT

In recent years, the increase in marine fuel prices coupled with stricter regulations on pollutant emissions set by the International Maritime Organization have promoted the research in new propulsion technologies and the utilisation of cleaner fuels. This paper describes a novel methodology to enable quantifying and evaluating the environmental and economic benefits that new technologies and fuels could allow in the marine sector.

The proposed techno economic and environmental analysis approach enables consistent assessment of different traditional propulsion systems (diesel engine and gas turbine) when operated in conjunction with a novel environmental friendly technology, such as a vertical axis wind turbine. The techno-economic and environmental assessment is focused on the potential reduction in fuel consumption and pollutant emissions that may be accrued while operating on typical *Sea Lines Of Communication* (Mediterranean, North Sea, Atlantic).

The study demonstrates the benefits of the installation of two vertical axis wind turbines on the deck of a ship in conjunction with conventional power plants. The analysis indicates that the performance of the wind turbines and the corresponding benefits strongly depend on the routes and environment in which they operate (therefore favourable wind conditions) allowing fuel savings from 14% (in the gas turbine case) to 16% (in the diesel engine case). The study also indicates that possible benefits may diminish for weak wind conditions.

The results reported in this paper establish the economic benefits of installing vertical axis wind turbines in conjunction with conventional technology (Diesel and Gas Turbine Power plants) when installed on a ship travelling through the Atlantic Ocean. The primary purpose of this study is to introduce a methodology to demonstrate the application, performance and economic benefits of the technology at a preliminary design phase and further form a foundation for more elaborate analysis on the subject in the future.

1. Introduction

Shipping is one of the most critical means of transportation for sustaining the global economy. It is an economical means for sustaining the international import and export markets whilst enabling global distribution of cargo. The rapid growth of global economies and the corresponding sharp rise in the requirement to transport large scale cargo has primarily been responsible for accelerated development of technology in the shipping industry over the last few decades.

The sustainability of the shipping industry, as any other industry, depends on the elasticity of demand for the service and the profitability through minimising operating costs. These costs in the past have largely depended on the price of marine fuels, but with environmental emissions now being in the forefront, this trend is set to change. A good example of this trend is the introduction of new environmental compliance standards through Marine Pollution (MARPOL) annex VI (Marine Environment Protection Committee, 2011) and the potential introduction of carbon taxes.

Assessing and understanding the interdependency and effects of environmentally optimised solutions and emission mitigation policies along with the adaptation of more fuel efficient solutions

* Corresponding author.
E-mail address: lorenzo.talluri@unifi.it (L. Talluri).

http://dx.doi.org/10.1016/j.oceaneng.2016.05.047
0029-8018/

Nomenclature

CNG	Compressed Natural Gas
COGOW	Climatology of Global Ocean Winds
dS	change distance
dt	change time
EES	Engineering Equation Solver
HAWT	horizontal axis wind turbine
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	liquid natural gas
MARPOL	Marine Pollution
MDO	Marine Diesel Oil
O&M	Operation and Maintenance
SFC	specific fuel consumption
TERA	Techno-economic Environmental Risk Analysis
TRL	Technology Readiness Level
V	velocity of the vessel
VAWT	vertical axis wind turbine
V_{ref}	reference wind velocity

Emissions

CO_2	carbon dioxide
NOx	Nitrogen oxide
SOx	sulphur oxide

Finance

$	Dollars
$/kW	Dollars per kilowatt
$/mmBTU	Dollars per million British thermal unit
$/t	Dollars per tonne
$/y	Dollars per year
CF_j	cash flow at year j
i	discount rate
I_0	initial investment
IR	inflation rate
IRR	internal rate of return
j	year number
M$	million Dollars
M$/y	million Dollars per year
n	total number of years
NBP	National Balancing Point
NPV	net present value
NPV_{20}	net present value at 20 years
PBT	Payback period

will be paramount. Consequently, research on environmentally sustainable marine propulsion solutions in recent years has endeavoured to address precisely these issues (García-Martos et al., 2013; Notteboom and Vernimmen, 2009). Studies have also shown that the current global marine propulsion could be improved through the introduction of new propulsion technologies and by the utilisation of cleaner fuels (Hirdaris et al., 2014; Vergara et al., 2012; Alfonsín et al., 2014).

1.1. Power plants in the marine environment

The power plants for marine propulsion are primarily heat engines. These comprise steam turbines, gas turbines and reciprocating engines which run on conventional thermodynamic cycles. The selection of power plants is influenced by a significant number of factors which may include technical requirements, economic criteria and political influence. Hence, it may determine the predominance of one system over the other. However, with the energy crisis of 1974 and the significant improvements in the diesel reciprocating engine technology, the utilisation of steam and gas turbine cycles in the marine power plants significantly reduced due to their lower efficiency (Woodyard, 2004).

It may be noted that even though the majority of commercial vessels are powered by diesel engines, (El-Gohary, 2013), the gas turbine power plant has played a predominant and critical role in the military sector. With significant improvements in gas turbine cycle efficiency now being realised, the marine commercial sector has now witnessed an increased exploitation and application of the technology. This has specifically been seen in fast ferries and fast cargo ships as a consequence of its characteristic high power to weight ratio.

1.2. New technologies and fuels

In recent years, a significant amount of research and a number of studies have been undertaken on new technologies and fuels in the context of marine power plants. Parker (2013) offers an overview of the future of marine propulsion and the novel propulsion technologies that may be considered. His research has indicated that these technologies (nuclear propulsion, batteries, fuel cells, superconducting electric motors, renewable energies, Organic Rankine Cycle and hybrid propulsion) will be necessary (and need to be significantly developed) in order to overcome the fuel consumption and environmental issues impact.

On similar lines and in order to ensure the future environmental sustainability of marine propulsion, a significant number of important studies have been undertaken. Some of these include research which propose the use of nuclear energy for merchant marine propulsion (Hirdaris et al., 2014), consider the possibility of the addition of a waste heat recovery system combined with a conventional power plant (Burel et al., 2013; Livanos et al., 2014) and highlight the necessity and thereby proposing the development of a renewable energy infrastructure for marine propulsion (Huaa et al., 2008).

Several studies have also been undertaken on the application of wind propulsion technologies for marine application as a renewable source of energy. Some of the key ones include those by Leloup et al. (2014), Traut et al. (2014), Rojon and Dieperink (2014) and Bergeson and Greenwald (1985).

Apart from environmental friendly technologies a significant amount of research has also been undertaken on cleaner fuels with an aim to develop possible solutions to reduce environmental emissions. Studies by Alfonsín et al. (2014) and Andrews and Shabani (2012) have highlighted the application of Hydrogen as a possible alternative for a sustainable propulsion system, while Brynolf et al. (2014) compare the environmental performance of liquefied natural gas (LNG) and several biofuels.

The burning of natural gas for marine propulsion however is not an innovative idea, as it has been previously used in LNG carriers. Natural gas can be employed in compressed (Compressed Natural Gas – CNG) or in liquefied form (Liquefied Natural Gas – LNG). CNG volume is 1% of the volume it holds at standard atmospheric pressure. It is compressed and stored at pressure of 200–250 [bar], commonly in high pressures cylinders. LNG attains an even higher reduction in volume and consequently, the energy density of LNG is 2.4 times that of CNG or 60% of that of diesel