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**Techno economic and environmental assessment of Flettner rotors for marine propulsion**

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**KEYWORDS**
Gas Turbine; Diesel Engine; Flettner rotor; Fuel Consumption; Pollutant Emissions



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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 |
| $Re_{\Omega}$ | 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] |
| $\beta$ | Angle between the vessel bow and the real wind direction [°] |
| $\varepsilon$ | Apparent wind angle [°] |
| $\mu_T$ | Flow dynamic viscosity [Pa-s] |
| $\rho$ | Density [$kg/m^3$] |
| $\omega$ | Frequency |
| $\omega'$ | Frequency for half peak value |
| $\omega_p$ | Peak frequency |
| $\Omega_T$ | 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 |


**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.

## 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 utilization 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. M.M., 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 by Parker, J (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, S.E. 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, F., et al., 2013; Livanos, G.A., 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, V., et al., (2014) and Andrews, J. (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, S., 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, R., et al., (2014) and Leloup R., et al. (2016). The work was focused on kite propulsion and considered an analytical method to assess fuel savings. Traut, M., 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, L., et al., 1985) Rojon, I., and Dieperink, C., (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, P.C., and Kunal, G., 2009; Lambrecht, M., et al., 1994), on horizontal-axis wind turbines (Bockmann, E., and Steen, S., 2011) kites and Flettner rotor technologies (Traut, M., 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.

**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 economics of the ship, Flettner’s attempts were largely considered a failure (Ahlborn, F., 1939).

This failure of the technology was also attributed to the fact that fossil fuels at the time were relatively cheaper. However given the fact that fossil fuels as a resource is limited and expensive, more environmentally optimised solutions are also being pursued and a renewed interest in this technology has now emerged. The company ENERCON has launched in 2010 the first prototype vessel using this technology. The vessel 'E-Ship 1' is equipped with 4 Flettner towers, which are 27 meters in height and have a diameter of 4 meters each. The performance of the towers is controlled through the rotational speed of each individual tower and the study reports a maximum fuel consumption reduction of almost 25% (ENERCON, 2013).

The physical principle behind the operation of a Flettner rotor is the Magnus effect. The Magnus effect was first described by Gustav Magnus in 1853, while investigating the trajectory deviation experienced during ballistic tests (Badalamenti, C. and Prince, S.A., 2008). After launch, as a projectile spins, a force is generated from the centre of the sphere or cylinder to a direction perpendicular to the axis of rotation (Zdravkovich, M.M., 2003). As a consequence the predicted trajectories of these projectiles were subject to deviations dependent on their direction of rotation. The force at the origin of these observed deviations is referred to as the Magnus effect. It results from the interaction of a cross flow on a rotating cylinder or a sphere. When the flow and the cylinder surface velocities are in the same direction the boundary layer around the cylinder is accelerated. On the other hand, when flow and cylinder surface velocities directions are in the opposite direction the boundary layer is decelerated. This is attributed to the formation of a thin boundary layer around the cylinder wall due to the viscosity of the fluid as highlighted by Prandtl (Prandtl, L., 1925). Due to this phenomena, the velocity difference generated near the cylinder surface leads to an asymmetrical pressure distribution. It is possible to correlate the pressure distribution to the velocity distribution around the cylinder through the Bernoulli equation along a streamline. When a stagnation point is reached, the pressure reaches its maximum value and curved flow patterns are generated around the cylinder. The corresponding pressure gradient is at the origin of the creation of a force directed from the point of maximum pressure to the point of minimum pressure. This therefore results in two forces being generated when a cylinder is in rotation in a cross flow (Ahlborn, F., 1939):

- The drag force that results from the interaction of the flow with a solid obstacle.

- The lift force, which results from the pressure difference around the cylinder.

This base model is useful in understanding the principles of this phenomenon; nonetheless, another determinant parameter, that is required to be taken into account, is the viscosity of the flow. The viscosity has a direct impact on the flow behaviour and alters its pattern. It is therefore necessary to consider a no-slip condition for the flow at the cylinder surface, which generates a skewed boundary layer that will have an impact on its three-dimensional pattern (Childs, P., 2010). Due to the complexity of this phenomenon, most of the studies related to the flow behaviour around a rotating cylinder are based on computational fluid dynamics (CFD) simulations and empirical correlations.

The earliest experiments were carried by Ludwig Prandtl in 1925. Prandtl concluded that when two stagnation points around the cylinder were mixed together, a theoretical maximum lift force was generated and this was equal to $4\pi$ (Prandtl, L., 1925). In the specific configuration where endplates were added at the end of the rotating cylinder, Prandtl also highlighted the dependence of the overall lift coefficient on the cylinder aspect ratio and the ratio between the apparent flow speed and rotating velocity of the cylinder.

At the beginning of the 21$^{th}$ century, a significant number of computational fluid dynamics based analyses were performed to determine the behaviour of the rotating cylinder at low Reynolds number. The contribution of research from Mittal and Kumar (Mittal, S., and Kumar, V., 2001) clarified the complex flow instabilities that are generated around such a cylinder. Recent studies have shown that for moderate values of Reynolds number ($Re = 3.8 * 10^3$), it is possible to exceed the theoretical lift coefficient limit imposed by the Prandtl theory (Seifert, J., 2012).

However, due to constraints linked to a maritime application of the Flettner towers, primarily being the sensitivity to wind speeds and cylinder diameters, it is necessary to investigate the behaviour of the flow around a rotating cylinder for large Reynolds number, above $10^6$. Therefore, in order to assess the performance of the Flettner rotor, the work in this research refers to experiments by Badalamenti (Badalamenti, C. and Prince, S.A., 2008). The experiments by Badalamenti are focused on CFD based investigations of a flow across a rotating cylinder at high values of Reynolds number. During this specific study it was shown that the lift and drag coefficients generated by the rotating circular cylinder are dependent on the cylinder diameter, on the Reynolds number and also on the free stream velocity. Badalamenti and Prince (2008) determined that the Reynolds numbers have an influence on the lift coefficient only when the ratio between the free stream and cylinder surface velocities are lower than 2. For velocity ratios higher than 2, the lift coefficient curves reach an asymptotic value, on which the Reynolds number then has a limited influence. Consequently, it is possible to assume that for Reynolds numbers above the behaviour of the lift coefficient curves will always be the same if the velocity ratios are kept above 2.

Another important result reported by Badalamenti and Prince (2008) is the possibility of determining the optimum rotor geometry required to have the best compromise between tower compactness and generated lift and drag coefficients. In particular the results from the work notably displayed that the optimum Flettner tower configuration is achieved when the endplate diameter is equal to twice the cylinder diameter. The endplate to cylinder diameter ratios are deemed responsible for a significant increase in the maximum reachable lift coefficient value.

**METHODOLOGY**

The main objective of this research was to develop a consistent methodology to evaluate the economic and environmental gain of installing Flettner towers on the deck of a vessel. Therefore, for the purposes of this study, the following key assumptions were made on the simulated routes, as well as on the stability of the vessel.

- The installation of the Flettner towers has been assumed not to have an impact on the vessel performance in terms of stability and maximum allowable vessel displacement. This additional weight is assumed to be offset by a lower cargo capacity.
- The investigated voyages for the vessel are assumed to follow linear and direct routes with no obstruction from weather or physical geographical entities.
- The vessel is assumed to always maintain maximum operating speed of 14.5 knots.

**TERA framework**

Techno-economic Environmental Risk Analysis (TERA) essentially comprises a framework of mathematical models to simulate the performance of a single or a set of technologies. The framework allows an increased visibility of risks, whilst enabling the user to compare and rank competing schemes on a formal and consistent basis, to enable efficient allocation of resources (Goulos, et al., 2010; Najafi Saatlou, et al., 2014; Doulgeris, G., et.al. 2012).

TERA has been extensively used in the past to conduct design space exploration, trade-off studies, parameter sensitivity analysis, asset management and multi-disciplinary optimisation (Kyprianidis, et al., 2011; Kyprianidis, et al., 2014; Xu, et al., 2013; Najafi Saatlou, et al., 2014; Camilleri et al., 2014). Frameworks that utilise a similar approach to TERA have also been used successfully by other researchers in the field for novel technology assessments (Marinai, L., et.al. 2004; Alexiou, et al., 2012). TERA has also been applied to marine propulsion system by Talluri et al. (2016).

This study utilises a TERA model framework to produce a set of performance, environmental and economic assessments in order to investigate a feasible and profitable solution for the reduction of gaseous emission and fuel consumption in the shipping industry.

The framework (figure 1) is modular in structure and consists of a set of core models, which allow simulation of performance of detailed power-plant systems, utilising robust mathematical models of components. The core models can be further coupled with a wide range of environment, economic and risk models. The modules utilised in this work have also been described in detail by Talluri et al. (2016). The current work however also includes an improved calm water resistance module, which takes into account the interactions of the vessel with regular waves.

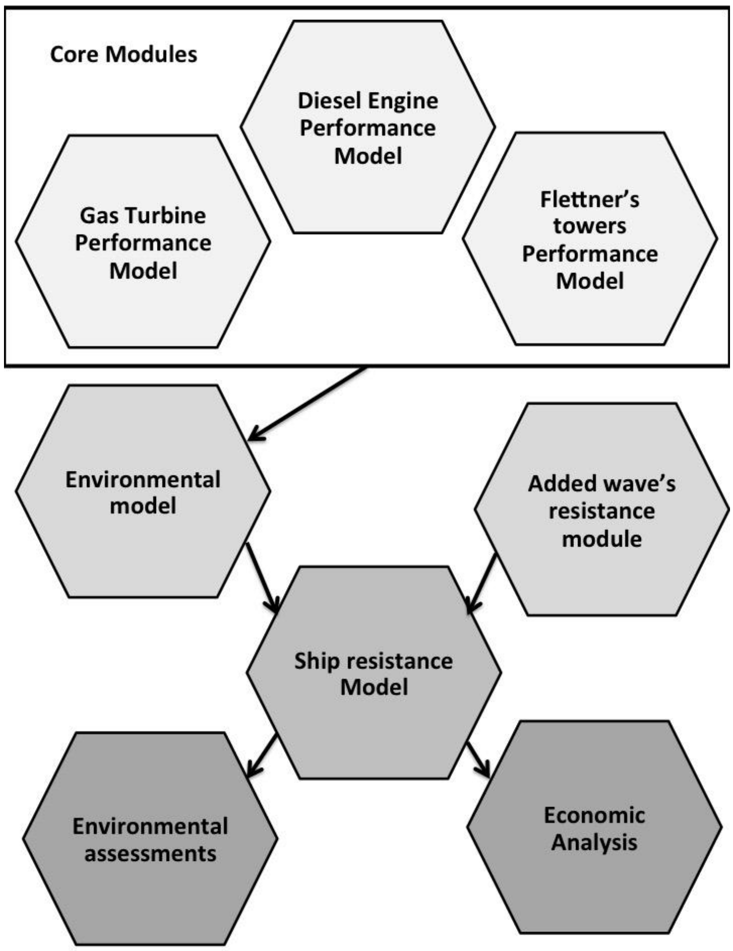


**Figure 1** Schematic of TERA framework

The TERA analysis initially requires a detailed definition of the technology being assessed and the platform it is being assessed on. In this case study, this entailed the selection of the class of ship to be used as a platform for the integration of the novel propulsion system. The marine vessel simulated in this study is based on the Dong-bang Challenger, a specialist ro-ro steel transporter (Lingwood, 1999). The real vessel is equipped with 2 diesel engines of 3 MW each. Furthermore, to enable integration of the Flettner towers, the deck of the ship is assumed to be free of obstructions. A detailed specification of the vessel can be found in Talluri et al. (2016).

The core modules included in the customised TERA framework used for this research enable the simulation of the performance of the marine vessel, gas turbine propulsion system, diesel engine propulsion system and Flettner tower technology. These modules are then further integrated with specialised modules to simulate atmospheric/ weather conditions for selected mission/routes, predict environmental emissions and analyse economic performance.

The performance of the gas turbine was simulated using an in-house gas turbine performance software *Turbomatch* (Macmillan, 1974) and was based on a 4.5 MW simple cycle, two-shaft marine gas turbine. The diesel engine performance model was based on the available information for the power plant (MAN B&W, 2013) installed on the reference ship. The fuel consumption of the diesel power plant was estimated using a simple correlation developed using the specific fuel consumption curve. This was done at a constant engine speed (750 RPM) and was obtained through linear interpolation of the reference diesel engine data (MAN B&W, 2013).

The ship resistance model has been presented in detail in (Doulgeris, G., et al., 2012) and (Talluri, et al., 2016). The model is divided into five sub-routines, which match the power available from the prime movers and the required power assessed through the hydrodynamic and aerodynamic resistance of the ship. The calculation of the total resistance of the ship enables the estimation of the power required by the installed prime movers on the vessel, in order to keep the desired velocity.

To determine the required propulsive power of the ship, the resistance model follows the *Holtrop and Mennen method*, (Holtrop, J., and Mennen, G.G.J., 1982). The aerodynamic resistance of the ship was simulated by applying the method proposed by Jensen (Schneekluth H., and Bertram, V., 1998) for the head wind case and the Blendermann model for all the other cases (Blendermann, W., 1993). The model does not however consider the hydrodynamic resistance effects of shallow water. The effects of propeller cavitation were also not taken into account within the scope of this work (Talluri, et al., 2016).

The gas turbine emissions ($CO_2$ and NOx) were predicted using an in-house emission prediction software which produced emission indices (Celis, C. 2010). The diesel engine NOx and $CO_2$ emissions predictions were based on data available in the public domain for the engine. The available literature suggests 560 - 620 [g/kWh] and 8 - 10 [g/kWh] for $CO_2$ and NOx respectively. The study assumes a mean value of the range indicated (MAN B&W, 2013; Marine Environment Protection Committee, 2009).

The atmospheric module, which predicts the ambient conditions, was based on a method that exploits the utilization of three cosine functions, each one simulating a day period, developed by (Huld, A.T., et al., 2006). The weather routine, which determines the wind speed and direction data, was based on the Climatology of Global Ocean Winds (COGOW) database and the data obtained from reports of Oregon State University's Cooperative Institute for Oceanographic Satellite Studies (Risien, C.,M., and Chelton, D.B., 2006).

The calm water resistance model has previously been described in detail (Talluri et al. 2016). An additional vessel resistance, which is derived from the interactions of the vessel with regular waves, has been added as an upgrade to the previous model in order to account for the fact that the combined waves and ship motions could result in a 20% to 40% increase in water resistance (Liu, S., et al., 2011). The scheme developed and described in reference (Alexandersson, M., 2009), has shown that it was possible to approximate the added resistance due to the wave's motion. However, it must be noted that linearized formulation of the "Gerritsma and Beukelman's method" (Gerritsma, J. and Beukelman, W. 1972) is only valid for head waves, for even keel vessels and when only radiation induced resistance is implied.

Alexandersson (Alexandersson, M., 2009) in his work has suggested a method to take into account the incident wave angles. This method was also adopted in the present study to estimate the wave resistance contribution. In particular, the added wave resistance is expressed as a normal distribution function (eqn. 1).

$$R_{AW} = R_{AW_p} * e^{-\frac{(\omega-\omega_p)^2}{2*c^2}} \tag{1}$$

Where c represents the "width" of the normal distribution function and can be expressed as function of the peak frequency and the frequency for which is equal to half its peak value (eqn. 2).

$$c = \frac{\omega_p-\omega'}{\sqrt{2*\ln 2}} \tag{2}$$

Furthermore, in order to simplify the linear regression analysis, the different parameters have been adapted to be dimensionless as shown in the following equations (eqn. 3 and eqn. 4).

$$\omega_{p_{ad}} = \omega_p * \sqrt{\frac{L}{2*\pi*g}} \tag{3}$$

$$c_{ad} = c * \sqrt{\frac{L}{2*\pi*g}} \tag{4}$$

All the parameters that impact the added resistance are summed up in table 1.

**Table 1 -** Added wave resistance determining parameters

| | Parameters | Dimensionless parameters |
|---|---|---|
| Waterline length [m] | L | 1 |
| Prismatic coefficient [-] | $C_p$ | $C_p$ |
| Longitudinal centre of gravity [m] | $L_{CG}$ | $L_{CB,norm} = \frac{L_{CG}}{L}$ |
| Beam [m] | B | $b_{norm} = \frac{b}{l}$ |
| Draught [m] | T | $T_{norm} = \frac{T}{L}$ |

| | | |
|---|---|---|
| Radius of pitch gyration [m] | $r_{yy}$ | $k_{yy} = \frac{r_{yy}}{L}$ |

The linear equations, which are used to predict the added resistance, are similar for all types of ships (eqn. 5, 6 and 7) However the different β are specific for each type of ship and can be found in reference (Alexandersson, M., 2009).

$$R_{AW_p} = \beta_{const} + \beta_{C_p} * C_p + \beta_{L_{CB,norm}} * L_{CB,norm} + \beta_{b_{norm}} * \frac{1}{b_{norm}^2} + \beta_{T_{norm}} * T_{norm} + \beta_{k_{yy}} * \frac{1}{k_{yy}^2} + \beta_{F_N} * F_N \quad (5)$$

$$\omega_{p,norm} = \beta_{const} + \beta_{C_p} * C_p + \beta_{L_{CB,norm}} * L_{CB,norm} + \beta_{b_{norm}} * b_{norm} + \beta_{T_{norm}} * T_{norm} + \beta_{k_{yy}} * \frac{1}{k_{yy}^2} + \beta_{F_N} * \frac{1}{\sqrt{F_N}} \quad (6)$$

$$c_{norm} = \beta_{const} + \beta_{C_p} * C_p + \beta_{L_{CB,norm}} * L_{CB,norm} + \beta_{b_{norm}} * b_{norm} + \beta_{T_{norm}} * T_{norm} + \beta_{k_{yy}} * \frac{1}{k_{yy}^2} + \beta_{F_N} * \frac{1}{F_N^2} \quad (7)$$

Finally, the modulation of the added resistance formula for different wave's incidence was obtained and described as follows (table 2).

**Table 2** Modulation of the added resistance formula for different wave's incidence (Alexandersson, M., 2009).

| Wave's direction [°] | Added resistance formula modulations |
|---|---|
| $\beta = 0$ (head waves) | No changes from eq. (6) |
| $0 < \beta \leq 90$ | $R_{AW_p}(\beta) = R_{AW_p} * \cos(\beta)$ |
| $90 < \beta \leq 180$ | $R_{AW_p}(\beta) = R_{AW_p} * \cos(\beta)$ <br> $\omega_p(\beta) = \frac{1}{2} * (\frac{g}{V * \cos(\pi - \beta)} - \sqrt{\left(\frac{g}{V * \cos(\pi - \beta)}\right)^2 - 4 * \left(\frac{g * \omega_p}{V * \cos(\pi - \beta)} - \frac{\omega_p^2}{\cos(\pi - \beta)}\right)}$ <br> $c(\beta) = \left(\frac{1}{\cos(\pi - \beta)}\right)^{\frac{1}{4}} * c$ |

**Flettner towers propulsive prediction module**

In order to estimate the power required to rotate a Flettner tower around its axis, as shown in equation (eqn. 8), studies undertaken by Theodorsen and Regier on the subject of rotating cylinders in laminar and turbulent flows were considered (Theodorsen, T., and Regier, A., 1944).

$$P_{req} = T_q * \Omega_T \quad (8)$$

Where $P_{req}$ is the power required to rotate the tower in Watts, $T_q$ is the tower frictional moment in Newton-metre and $\Omega_T$ is the cylinder rotational speed in rad/s. The rotational speed can be obtained directly from the velocity ratio and apparent wind velocity. The moment coefficient, on the other hand, has to be determined to estimate the frictional drag, as displayed (eqn.9).

$$T_q = \frac{1}{2} * C_{mc} * \pi * \rho * \Omega_T^2 * \left(\frac{d_t}{2}\right)^4 * L_T \quad (9)$$

An empirical correlation was derived for turbulent flow around a rotating cylinder without the contribution of endplates. In this study it is assumed that the frictional drag induced by the presence of the discs is negligible compared to the main frictional drag. Following previous assumptions, eqn. 10 can then be adopted to find a convergent solution for the moment coefficient, based on the rotational Reynolds number. An initialisation of $C_{mc}$ of 0.02 is necessary to produce accurate results, as suggested in reference (Childs, P., 2010).

$$C_{mc} = \left(\frac{1}{-0.8572+1.25*\ln\left(Re_\Omega*\sqrt{C_{mc}}\right)}\right)^2 \quad (10)$$

The rotational Reynolds number can be estimated from equation (eqn. 11).

$$Re_\Omega = \frac{\rho_T*\Omega_T*d_T^2}{2*\mu_T} \quad (11)$$

In this research, following guidelines provided by reference (Badalamenti, C. and Prince, S.A., 2008), the Flettner towers were chosen to be designed with the dimensionless geometrical characteristics presented in table 3. In particular, these values were taken as reference case studies in order to compare the model developed with the literature. The aspect ratio value was assumed to be 5.1, as the simulation data available was specific to cylinders with this aspect ratio. The velocity ratio and the values for endplate to cylinder diameter ratio corresponds to the point for which the lift and drag coefficients reach asymptotic values. Therefore, the lift and drag coefficients that related to velocity ratio 3.6 are equal to 10.4 and 3.56, respectively.

**Table 3** Flettner towers specific features

| Towers features | Values |
|---|---|
| Aspect Ratio | 5.1 |
| Endplates to cylinder diameters ratio | 2 |
| Velocity ratio | 3.6 |

Based on these geometrical features, the design of the Flettner rotors was undertaken. The performance was calculated assuming implementation of three towers on the vessel. In order to space the rotors adequately, a spacing distance equal to the height of one tower was selected thereby assuming avoidance of aerodynamic interference from each other. It is also assumed that each tower is able to reach its full power capacity, however, in order to reflect real operating conditions the following considerations had to be made in the utilisation of the model:

- In head wind conditions all the towers are shut down and are assumed to act as additional wind resistance surfaces
- In a tail wind configuration, if one tower is not entirely surrounded by the wind flow due to the presence of the bridge structure, then it is shut down and considered to act as an additional wind resistance surface
- If the total power needed to rotate the towers is superior to the total propulsive gain, then all the towers are shut down and considered to act as additional wind resistance surfaces
- If the resultant forces generated by the towers are directed against the vessel's direction of motion, then the towers are shut down and are considered to act as additional wind resistance surfaces

Apart from the conditions stated above, all towers rotate and generate a propulsive force that counteracts the global water resistance related to the ship motion. To simulate the performance of the Flettner towers, velocity triangles displayed in the figure 2 have been utilised in order to determine the orientation of the lift and drag forces corresponding to the direction of movement of the vessel.

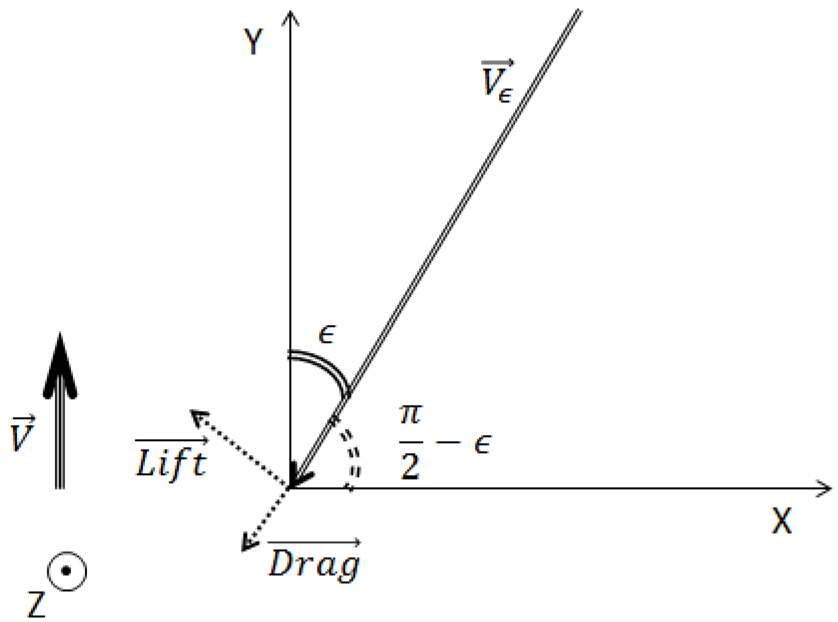


**Figure 2** Flettner towers vectors

The lift and drag coefficients have been derived from the (Badalamenti, C. and Prince, S.A., 2008) and as indicated (eqn. 12 and 13).

$$\mathrm{Lift} = \frac{1}{2} * \rho_{air} * A * V_\epsilon^2 * C_L \tag{12}$$

$$\mathrm{Drag} = \frac{1}{2} * \rho_{air} * A * V_\epsilon^2 * C_D \tag{13}$$

One of the main assumptions made is that only the resultant force component applied in the Y direction (direction of travel of the vessel) has been weighed. It is considered that the force components in the X direction have no impact on the vessel performance. The projection of the resultant force in the Y axis (in the reference frame O;X;Y;Z) is specified in eqn. 14.

$$\text{Resultant}_{\text{force}} = \text{Lift} * \cos\left(\frac{\pi}{2} - \epsilon\right) - \text{Drag} * \sin\left(\frac{\pi}{2} - \epsilon\right) \qquad (14)$$

**Economic analysis**

The aim of the research is to compare different propulsive technologies, and hence the economic study has been focused on the estimation of the costs incurred in propulsion of the vessel. As a consequence, it is possible to distinguish three primary constituents of costs:

- The capital cost that takes into account the initial cost of the different technologies;
- The operating and maintenance costs that consider the cost of fuel consumption and the annual maintenance;
- The emissions costs

The following six different propulsive configurations have been investigated in this analysis:

- Vessel utilising only a natural gas fuelled gas turbine as propulsion system
- Vessel utilising a natural gas fuelled gas turbine as propulsion system in conjunction with 3 meter diameters Flettner towers
- Vessel utilising a natural gas fuelled gas turbine as propulsion system in conjunction with 5 meter diameters Flettner towers
- Vessel utilising only a marine diesel oil fuelled reciprocating engine as propulsion system
- Vessel utilising marine diesel oil fuelled reciprocating engine as propulsion system in conjunction with 3 meter diameters Flettner towers
- Vessel utilising marine diesel oil fuelled reciprocating engine as propulsion system in conjunction with 5 meter diameters Flettner towers

From references (Goldstein, L., et. al., 2003), (Theotokatos, G., and Livanos, G., 2013), (Di Lorenzo, et. al., 2012), (Dimopoulos, et al., 2006) and (Charlier, R.H., and Justus, J.R., 1993) and depending on the size and scale of the technology, it was possible to assume an initial estimation of the capital prices (table 4) of a gas turbine, a reciprocating engine and a Flettner rotor. The data available also provided information on operating & maintenance costs (table 5) of a gas turbine and a reciprocating engine based on their rated power outputs. For the purposes of the study, it has been assumed that the Flettner rotor operation and maintenance costs would be negligible compared to those of the gas turbine and the diesel engine.

**Table 4** Capital costs estimation (Goldstein, L., et. al., 2003), (Theotokatos, G., and Livanos, G., 2013), (Di Lorenzo, et. al., 2012), (Dimopoulos, et al., 2006) and (Charlier, R.H., and Justus, J.R., 1993)

| Technology | Prices | Units |
|---|---|---|
| Gas Turbine | 3.48 | Million $ per unit |
| Reciprocating engine | 1.86 | Million $ per unit |
| 3m diameter rotors | 0.3 | Million $ per unit |
| 5m diameter rotors | 0.5 | Million $ per unit |

**Table 5** Operating and maintenance costs estimation (Goldstein, L., et. al., 2003)

| Systems | Operating & Maintenance costs | Units |
|---|---|---|
| Gas Turbine | 0.0059 | $/kWh |
| Reciprocating engine | 0.0079 | $/kWh |

In order to estimate the cost of the fuel used on different propulsion systems, it was necessary to implement a fuel cost forecast model in this economic module. Based on (IEA, 2016) forecast, it is possible to make a preliminary estimation of the evolution of the LNG and MDO fuel prices (Figure 3 and 4).

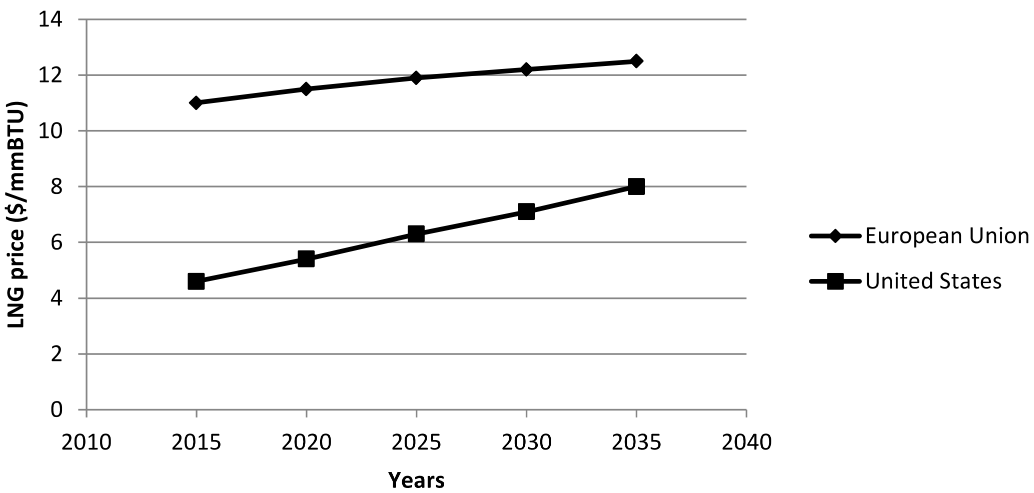


**Figure 3** International LNG price forecast (IEA, 2016).

Figure 3 displays the predicted price of LNG in the United States and European Union markets. The difference in prices between the US and Europe is attributed to greater availability of LNG in the United States compared to the European countries. In this research, it was also assumed that the fuel price related to one specific journey was equal to price of the fuel available at the start of the voyage. Furthermore, to simplify the model, it was also further assumed that the price of LNG in South-American countries was equivalent to the European market. For the prediction of the Marine Diesel Oil price, a global price was considered for all the different journeys. It is expressed in term of $/ton of MDO as displayed in the Figure 4. It may also be additionally noted that in order to make LNG more comparable with MDO it was necessary to express the LNG price in $/ton and hence assumptions were made to approximate the properties of natural gas.

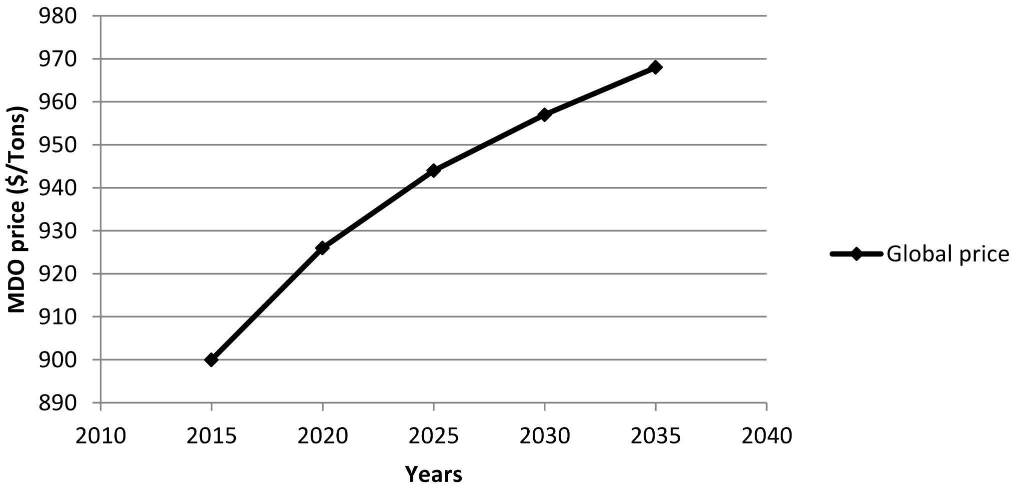


**Figure 4** International MDO price forecast (IEA, 2016).

The economic analysis also demonstrates the effect of the implementation of $CO_2$ emission taxation. Two different scenarios have been investigated in order to simulate the impact of such legislations on this sector. In the first scenario, it was assumed that the taxation rates on the $CO_2$ emissions are equivalent for both natural gas and MDO fuels in order to determine the possible existence of a specific tax rate for which one system configuration will become more advantageous than the other. In the second scenario, the legislation proposed by the British Columbia ministry of finance for motor fuel has been used (Ministry of Finance, British Columbia, 2013). It may be noted that this current legislation is specially designed to favour the utilisation of natural gas instead of oil as main fuel supplies. The different carbon taxation rates can be found in table 6.

**Table 6** Motor Fuel and Carbon Tax Rates (Ministry of Finance, British Columbia, 2013).

| Rates on Motor Fuels – Effective April 2013 | |
|---|---|
| Type of fuel | Carbon tax rate |
| Marked Gasoline | 0.06140 $/l |
| Marked Diesel | 0.07061 $/l |
| Locomotive Fuel | |
| Marine Diesel Fuel | |

| | |
|---|---|
| Marine Gas Oil | |
| Marine Bunker Fuel | 0.08700 $/l |
| Aviation Fuel | 0.06794 $/l |
| Jet Fuel | 0.07208 $/l |
| Propane | 0.04253 $/l |
| Hydrogen | - |
| Natural Gas | 0.00005 $/l |

The economic analysis is based on the concepts of actualized costs. The actualised costs model is one of the key metrics utilised by the industry for evaluating investments. It is calculated through (eqn.15) and it was chosen as it guarantees an immediate estimation of the gain derived by the installation of the Flettner rotors.

$$AC = \sum_{j=1}^{n} \frac{Costs_j}{(1+i)^j} \quad (15)$$

Where:

- $Costs_j$ = Costs at year j
- $i$ = Discount rate
- j = Year
- $n$ = Number of years the asset is assumed to be utilised

The study assumes a discount rate of 10 %, as suggested by references (Theotokatos and Livanos 2013; Livanos et al., 2014).

**ANALYSIS AND RESULTS**

**Flettner rotor power prediction**

Figure 5 indicates an estimate of power produced by a Flettner tower, which is 3m in diameter. It can be seen that when the vessel speed is equal to 14.5 knots, the optimum angle is not equal to 90°, but increases to 110°. The study indicated that, for optimum performance, wind incidence needed to be between 100° and 130°. With wind velocities reaching high values of 45-50 knots, the Flettner tower provided a propulsive contribution of more than 2 MW. It was also observed that for assumed sea state configuration, wherein the wind velocity was between 20 and 30 knots, the maximum power output that can be reached is lower than 1 MW and will therefore have a significant impact on the overall performance of the power plant.

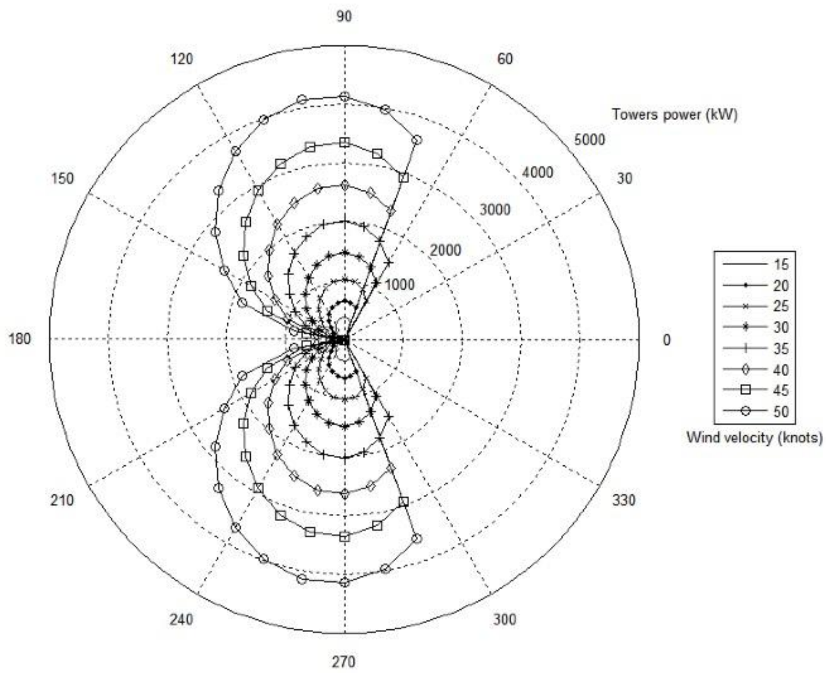


**Figure 5** Flettner tower, of 3 meter diameter, power generation, varying with the real wind velocity and incidence (with 0° in front wind) for V = 14.5 knots.

Another important parameter, which directly influences the lift and drag forces is the diameter of the tower. In order to initially validate the performance of the model and ensure that the indicative results produced were realistic in terms of demonstrating the effect of diameter, a comparative analysis was undertaken. Traut, M., et al., (2014) in their study have provided data for a Flettner tower of diameter 5m and a height of 35 m. This was reported for a specific operating condition wherein velocity of the wind and ship were reported to be 20 and 19.4 knots respectively. Assuming similar test conditions and utilising the model developed, a simulation of a tower of diameter 5m was undertaken and results compared. The maximum power predicted by the model was 1.3 MW, in comparison to 1.5 MW reported in reference (Traut, M. et. al., (2014)) which was considered reasonably good match and adequate for the purposes of this study.

For the three towers combination selected, figure 6 indicates the maximum propulsive power contribution that may be achieved for varying tower diameters. Based on the characteristics of the curve, it may be inferred that this parameter has a significant influence on the performance of the Flettner towers and contribution to overall power generated. An increase of 10% in the tower diameter results in 19% increase of the maximum propulsive power contribution reachable.

Apart from the performance, the height of the tower will also be affected by the increase in diameter, in order to keep the right aspect ratio, and this would consequently have an impact on the ship's stability. While it is understood that the consequences of those modifications may have an effect, quantifying their sensitivity was considered beyond the scope of the work and hence it is assumed that the effect on the performance will be negligible in the current context.

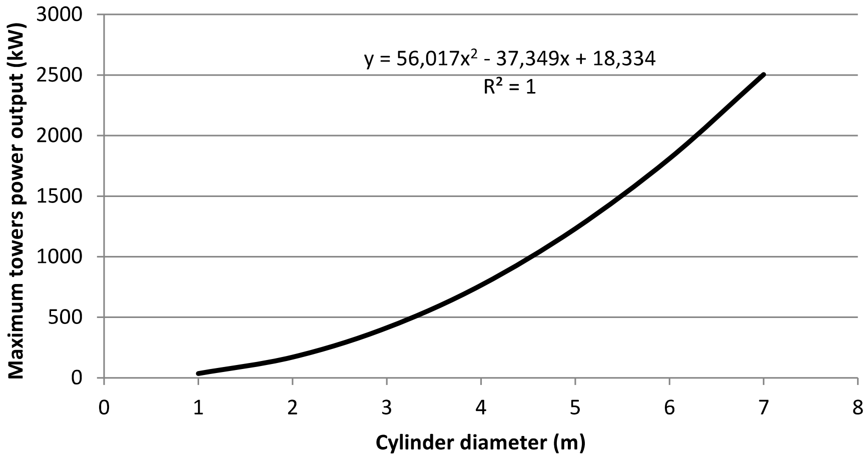


**Figure 6** Influence of the cylinder diameter on the maximum propulsive power contribution for V =14.5knots and Velocity of the wind of 20 knots.

**Route analysis**

The overall performance of the vessel along different voyages/routes (as listed in table 7) between selected ports has been analysed. The cumulative analysis of the performance has been undertaken over a period of 1 year. Maximum utilisation of the asset was assumed and hence the duration required to charge, discharge and maintain the vessel was estimated to be 1 day per shipping journey. The asset was also assumed to be operated for a maximum of 330 days per calendar year. The estimated number of trips achievable assuming the ship is consistently operated on a specific route is as listed in table 7.

**Table 7** Number of voyages per year

| Journeys | Annual utilisation (trips) |
|---|---|
| Route 1 (Livorno, Italy – Barcelona, Spain) | 82 |
| Route 2 (Southampton, United Kingdom – Oslo, Norway) | 60 |
| Route 3 (Southampton, United Kingdom– New York, United States of America) | 18 |
| Route 4 (New York, United States of America – Pecem, Brazil) | 16 |

**Environmental results**

**Emissions and fuel consumption analysis, Route 1 (Livorno, Italy – Barcelona, Spain)**

Figure 7 indicates the fuel burn incurred by the vessel and environmental emissions ($CO_2$ and $NO_x$) while operating over a period of one year on the Mediterranean route. It is observed that the gas turbine power plant releases more $CO_2$ than the reciprocating engine as it utilises a greater quantity of fuel. This is attributed to the fact that the gas turbine fuel burn is higher due to the overall lower efficiency compared to the reciprocating engine. Due to the lower efficiency, the gas turbine operated with natural gas produces approximately 18% higher $CO_2$ emissions when compared to the reciprocating engines burning MDO. It is also opined that in order to mitigate this effect the utilization of a recuperated cycle gas turbine would be considerably beneficial and aid in reducing the emission gap between these technologies.

While the application of the gas turbine is disadvantageous in terms of $CO_2$ emissions, it has an improved performance in terms of $NO_x$ emissions when compared with the diesel power plant burning MDO resulting in a reduction of 83%.

Analysis of figure 7 also indicates that the wind conditions along the Mediterranean trip are favourable for the implementation of the Flettner towers and therefore results in a noticeable impact in overall fuel consumption and environmental emissions. It is also observed that the Flettner towers have a more important impact in the reduction in $CO_2$ when they are combined with reciprocating engine instead of gas turbine; on the other hand, the impact on reductions in $NO_x$ emissions is comparable for both power plants (table 8).

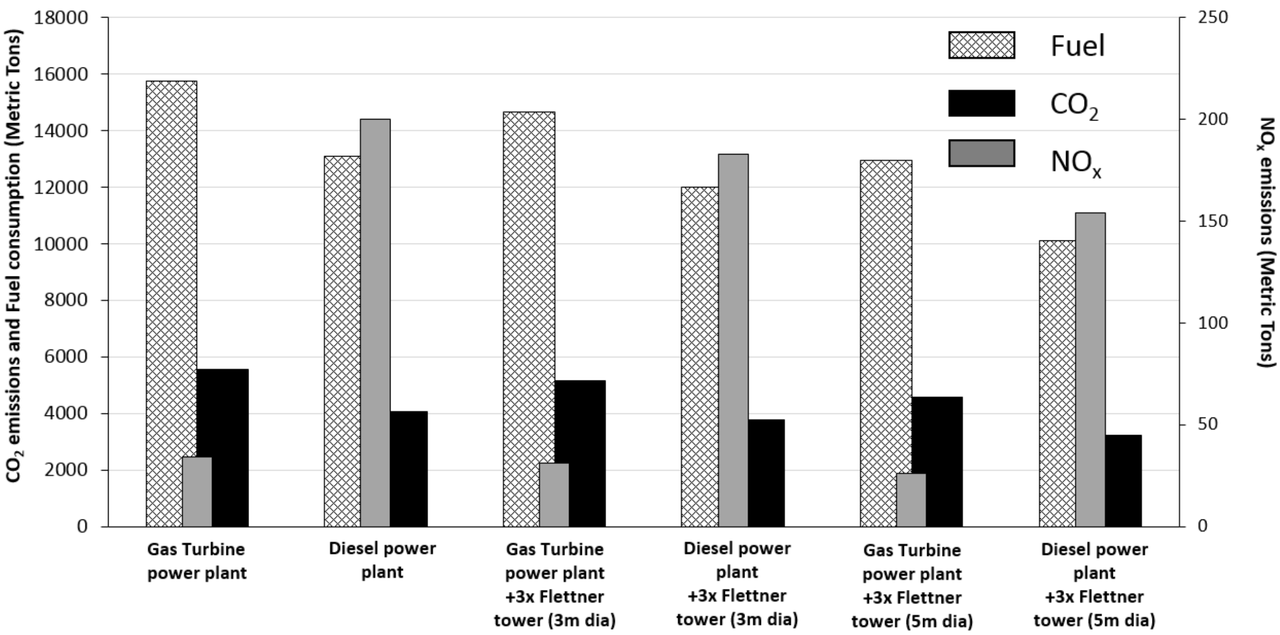


**Figure 7** Comparison of fuel burn and emissions ($CO_2$ and $NO_x$) for Route 1(Livorno, Italy – Barcelona, Spain)

**Table 8** Global exhausts gas emissions reduction compared to the configuration without towers, for the Mediterranean case study

| | | Exhausts gas emissions reduction (%) | | | |
|---|---|---|---|---|---|
| | | $CO_2$ | | $NO_x$ | |
| | | Gas Turbine power plant | Diesel power plant | Gas Turbine power plant | Diesel power plant |
| Towers Diameters | 3m | -6.94% | -8.24% | -8.82% | -8.50 % |
| | 5m | -17.77% | -22.77% | -23.53% | -23.00 % |

The results also indicated the extent of impact the diameter of the tower has in improving the efficiency of the propulsion system, and consequently on the overall the fuel consumption and environmental emissions. The fuel consumption reduction achieved when utilising 5 meters diameter Flettner towers is over 20% in the Diesel power plant configuration and almost 18% in the gas turbine power plant configuration (table 9). It is also similar to the reduction (25%) in fuel burn claimed by the study on the ENERCON E-ship 1 (ENERCON, 2013).

**Table 9** Global fuel consumption reduction compared to the configuration without towers, for the Mediterranean case study

| | | Fuel consumption Reduction (%) | |
|---|---|---|---|
| | | Gas Turbine power plant | Diesel power plant |
| Towers Diameters | 3m | -6.98% | -6.96% |
| | 5m | -17.84% | -20.41% |

For the others routes investigated, the emissions and fuel consumption reduction results have similar trends with minor variations attributed to changing ambient conditions.

**Comparison of environmental emissions for different trading routes**

Figure 8 provides the quantified assessments of $CO_2$ saving for the four selected propulsive configurations on each specific route. The comparative assessment has been made against the reference case, where the vessel is propelled without the implementation of the Flettner towers. It can be noted that, in terms of $CO_2$ emission reduction, routes in the Mediterranean and between the United States and Brazil are the most productive for the application of the novel technology. This is attributed to favourable wind intensity and direction encountered. The analysis also indicated that the wind direction has a greater impact on the performance of the propulsion system than the wind speed. The implementation of the Flettner towers enabled a promising 23 % reduction in $CO_2$ emission. The result also indicated lower benefits during unfavourable wind conditions.

Similar trends are observed for $NO_x$ emissions, as indicated in figure 9. Utilisation of towers with diameter of 5m delivered a reduction of up to 25 % in NOx emission reduction, when using it in conjunction with a gas turbine power plant as the main propulsive engine.

The overall analysis indicated that utilisation of the Flettner tower in conjunction with a Diesel power plant produced greater benefits in terms of reduction in fuel burn and $CO_2$ emission and comparable reductions in terms of NOx emission, when compared with its utilisation with gas turbine power plants.

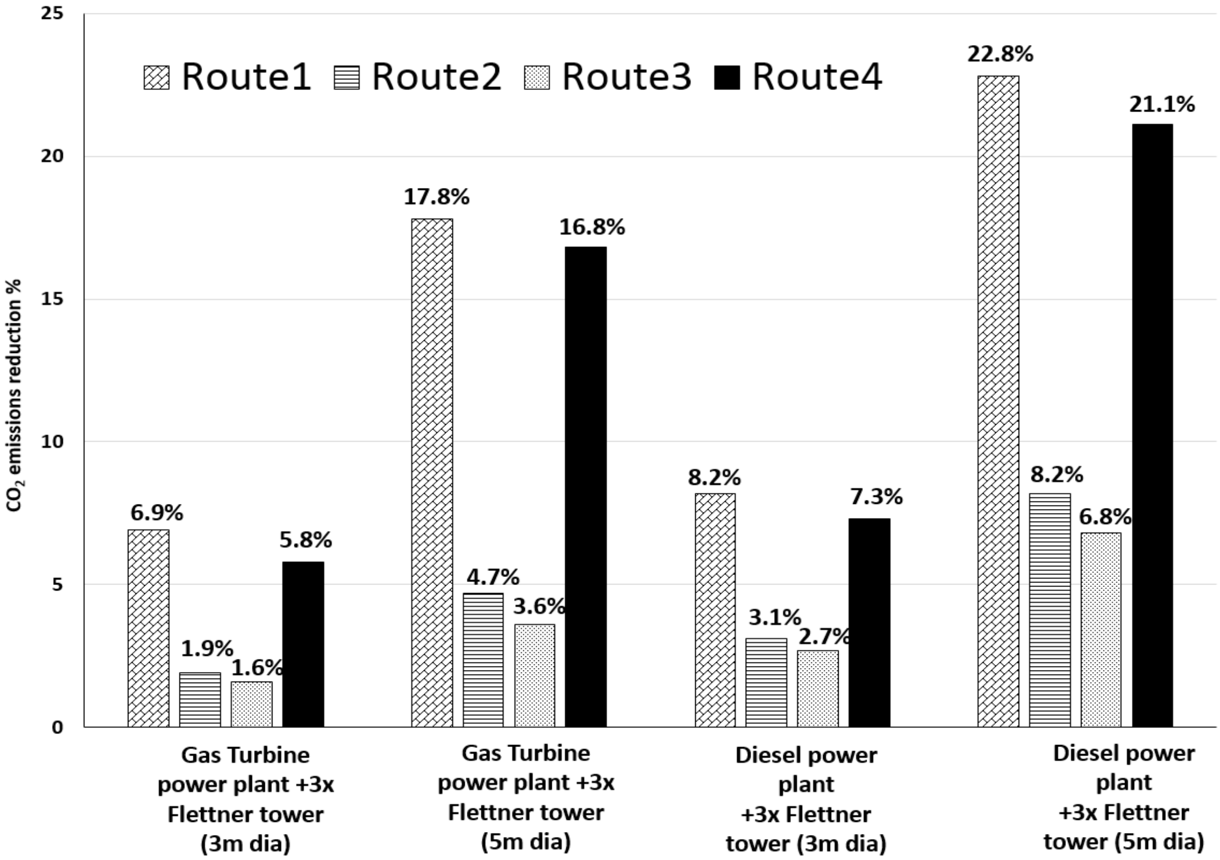


**Figure 8** Comparison of $CO_2$ emissions for specific routes analysed

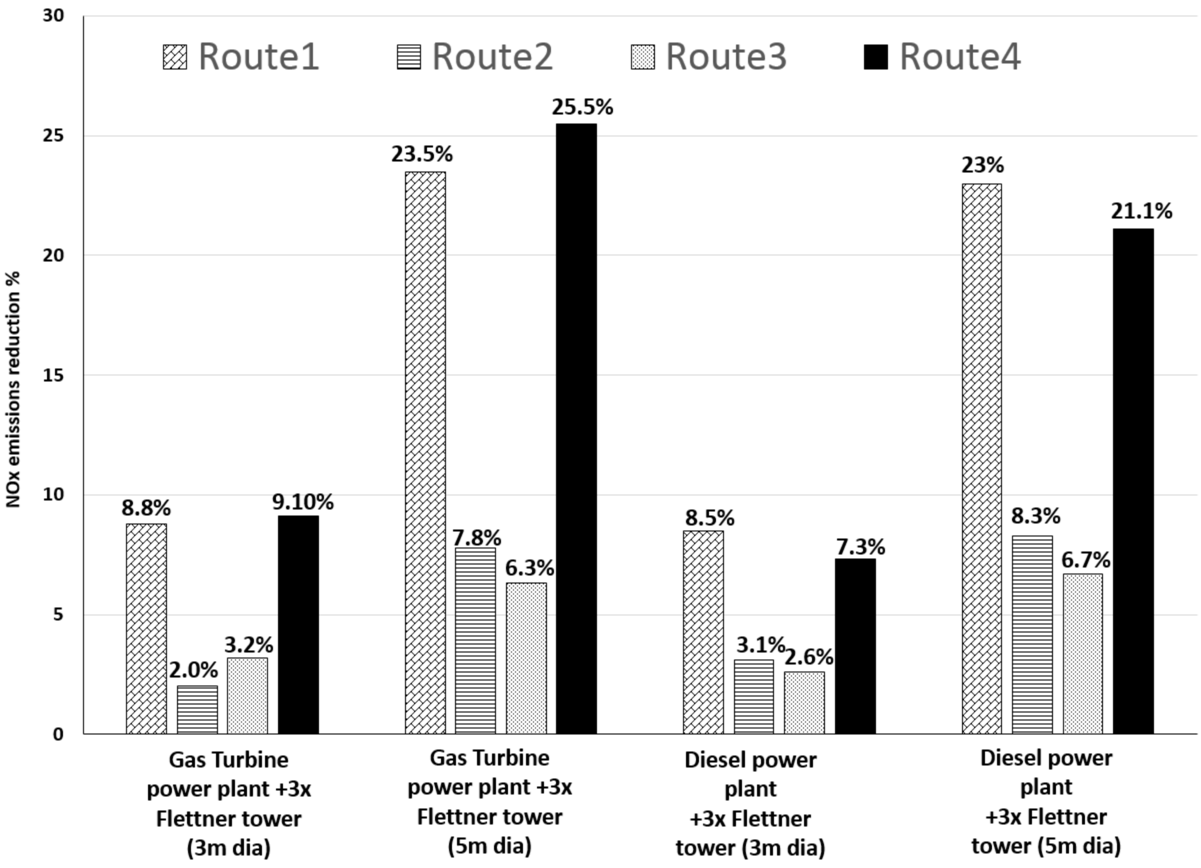


**Figure 9** Comparison of $NO_x$ emissions reduction for specific routes analysed

**Economic analysis**

The results obtained from two different economic scenarios have been discussed in this section. The main objective is to assess the economic viability of the different propulsive configurations and to determine the effect of the previously established environmental benefit.

**First scenario: same $CO_2$ emissions taxes**

For the Mediterranean route, Figure 10 displays the actualised costs of the different propulsive configurations analysed over 20 years of operation and as a function of the $CO_2$ emission taxes. The economic effect of emission taxation is directly dependent on the $CO_2$ emissions produced and the level of taxation per unit ton of emission produced, therefore, some configurations would benefit over the other depending on the applied rate of emission taxation. The analysis of the Mediterranean route, as indicated in figure 10, denotes that for any $CO_2$ taxation levels less than 200 $/ton, the diesel power plant without the application of Flettner towers is not competitive. However when higher taxation rates are applied, the gas turbine power plant configuration also results in being the least economically desirable, in comparison to other technologies considered.

In terms of operational economics, the configurations, which include Flettner towers with wide diameters (5m) coupled with either diesel engine or the gas turbine, are the most favourable. Specifically, gas turbine configurations are more suitable for $CO_2$ taxation rates under 110 $/ton while the configurations utilising diesel engines are better for higher taxation rates. This is attributed to comparatively higher levels of $CO_2$ emissions from the gas turbine configuration compared to the diesel power plant configuration as discussed earlier.

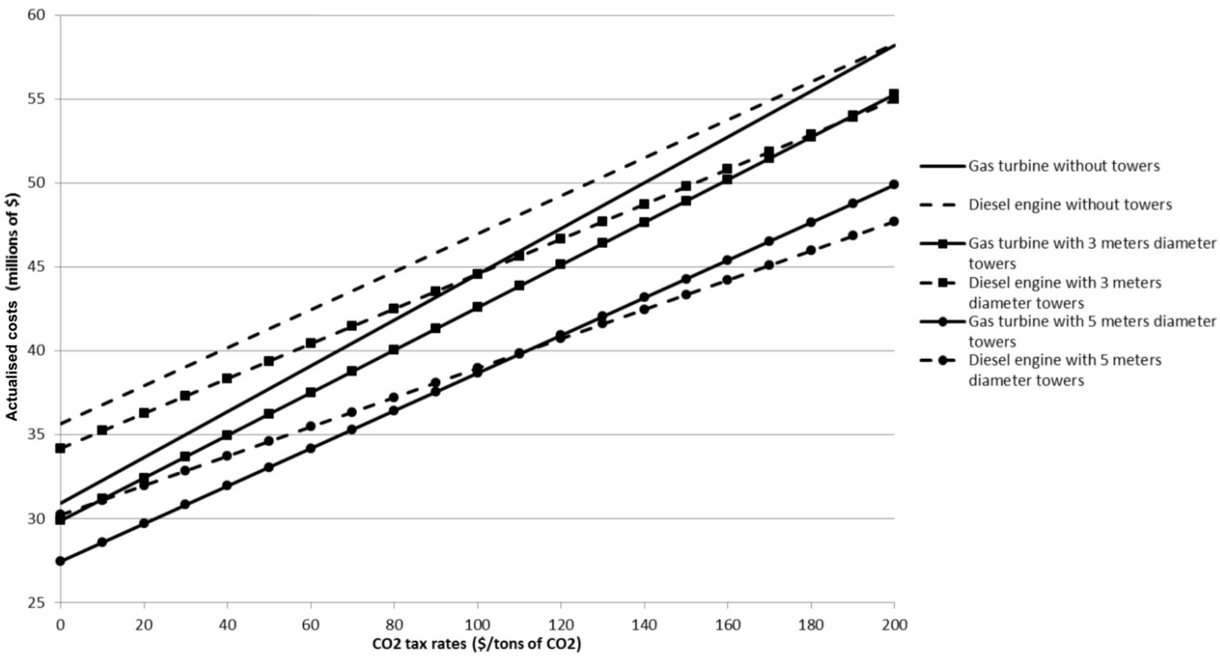


**Figure 10** Influence of the $CO_2$ tax rates on the economic viability of the different propulsive configurations for the first route (Mediterranean)

In the case of the second route selected (United Kingdom to Norway), as seen in figure 11, the trend was found to be completely different from the previous case study. The best configuration is found to be the gas turbine power plant without Flettner towers. This is due to the low propulsive power contribution of the Flettner rotors over the route. However it was observed that utilisation of a diesel power plant in conjunction with Flettner towers provided economic benefit as the taxation rate was increased. It is opined that for the prevailing scenario, wherein no $CO_2$ taxation policy has been implemented, the implementation of Flettner towers on a ship for this route is unviable, as it provides no economic benefit.

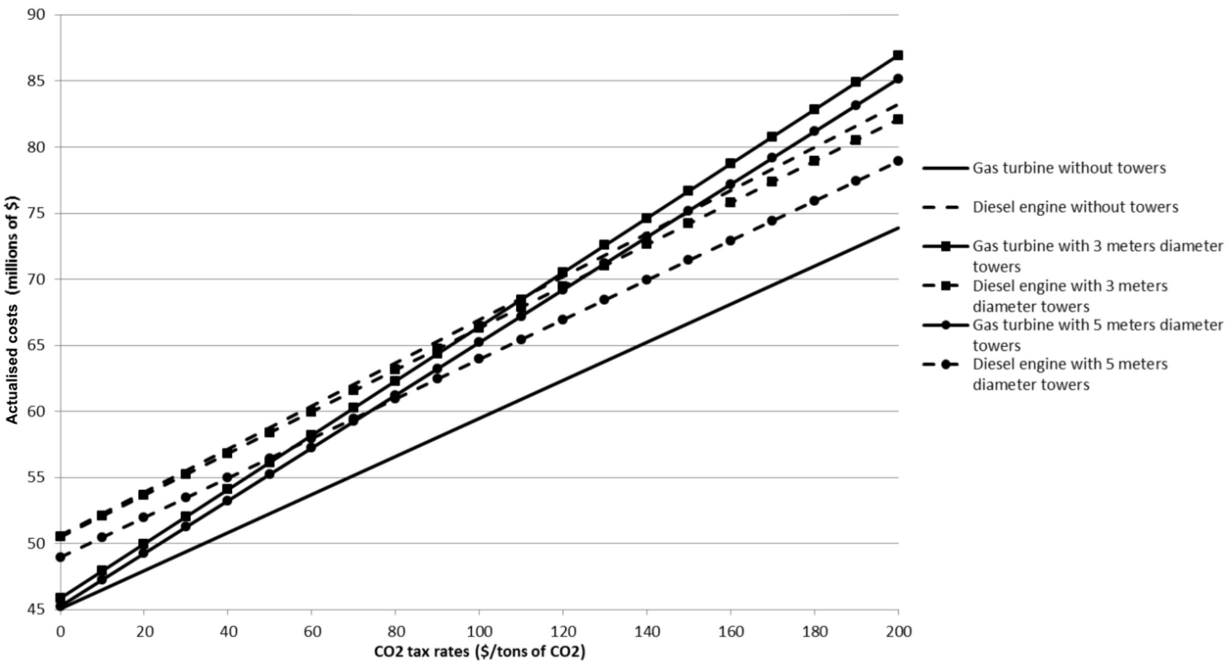


**Figure 11** Influence of the $CO_2$ tax rates on the economic viability of the different propulsive configurations for the second route (North Sea)

In the case of the third route (North Atlantic voyage), as seen in figure 12, it can be noted that for the range of $CO_2$ taxation rates investigated, all the gas turbine configurations were economically better than configurations utilising diesel engines. The implementation of the Flettner towers however is more beneficial on the diesel engine configuration and produced some economic benefit.

For the fourth route considered (United States to Brazil), as seen in figure 13, trends similar to the first case are observed. Gas Turbine configurations, with and without Flettner towers, are significantly more cost effective. However only after $CO_2$ taxation rates of above 140 $/tons does the diesel engine configuration with 5 m Flettner towers begin to appear competitive.

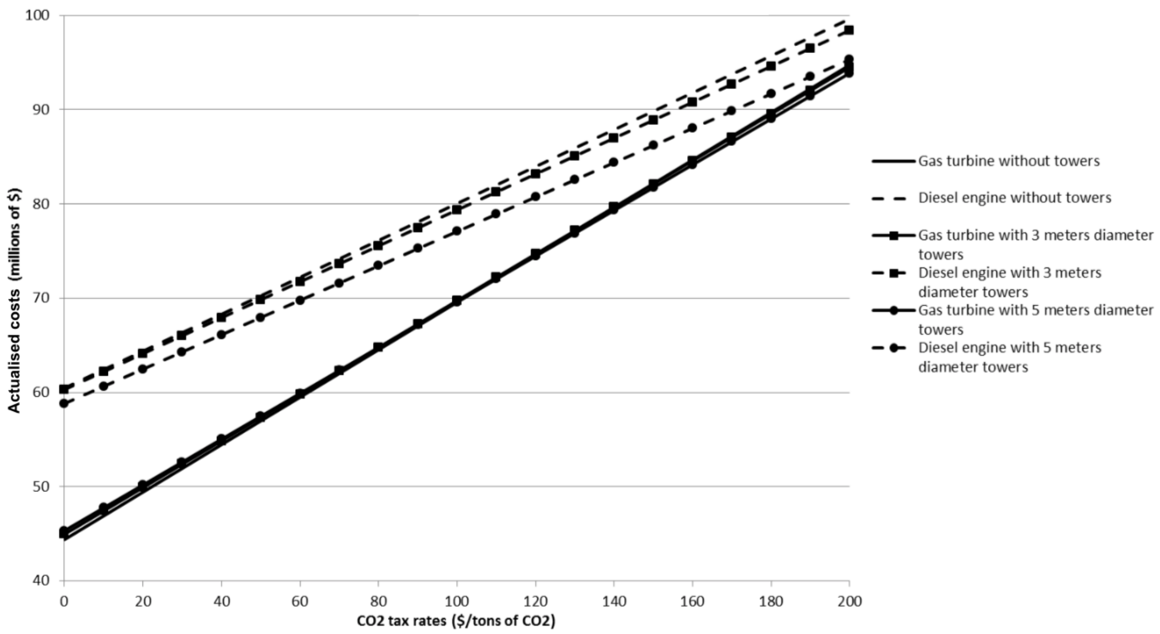


**Figure 12** Influence of the $CO_2$ tax rates on the economic viability of the different propulsive configurations for the third route (North Atlantic Ocean)

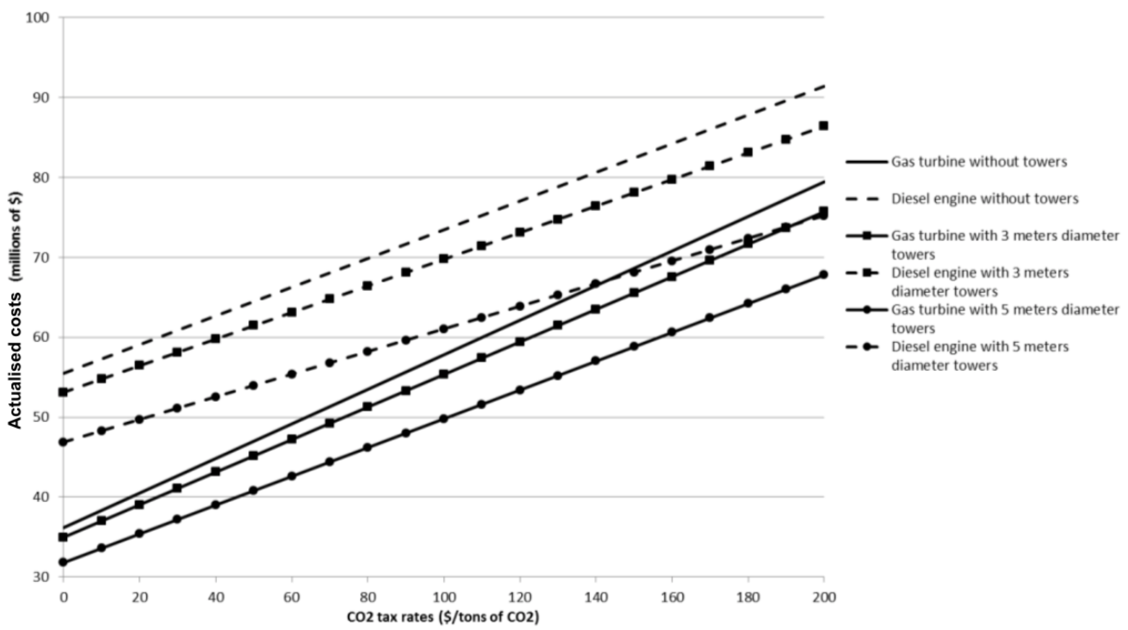


**Figure 13** Influence of the $CO_2$ tax rates on the economic viability of the different propulsive configurations for the fourth route (North to South Atlantic Ocean)

**Second scenario: British Columbia taxes**

The second scenario analysed is based on the British Columbia environmental legislations and emission taxation rates. In addition to the global reduction of the emissions, the main objective of this legislation is to promote the utilisation of natural gas over diesel fuel and clearly indicates the effect environmental legislations may have in the consideration of novel technology. Figure 14 shows the different actualised propulsive costs over a period of 20 years of operation.

Analysis of the chart indicates that as a consequence of the prevalent environmental legislation and consequently low cost of natural gas in comparison to MDO, depending on the route analysed, the gas turbine propulsion system fares significantly (45-95%) better than the diesel engine.

Further depending on the route selected and the wind and atmospheric conditions this benefit can be further increased. The analysis also indicated that if an operator were considering only a diesel power plant, the benefits of implementing a Flettner tower would be greater. The implementation of a set of 3 Flettner towers (5 m diameter) provides a reduction in costs from 3-17%. However the economics of implementation of the towers in conjunction with a gas turbine systems is found to be significantly lower and for some routes (2 and 3) even detrimental in some cases.

As a conclusion of this economic analysis, even if the Flettner towers have always a positive environmental impact, their implementation is not always economically viable.

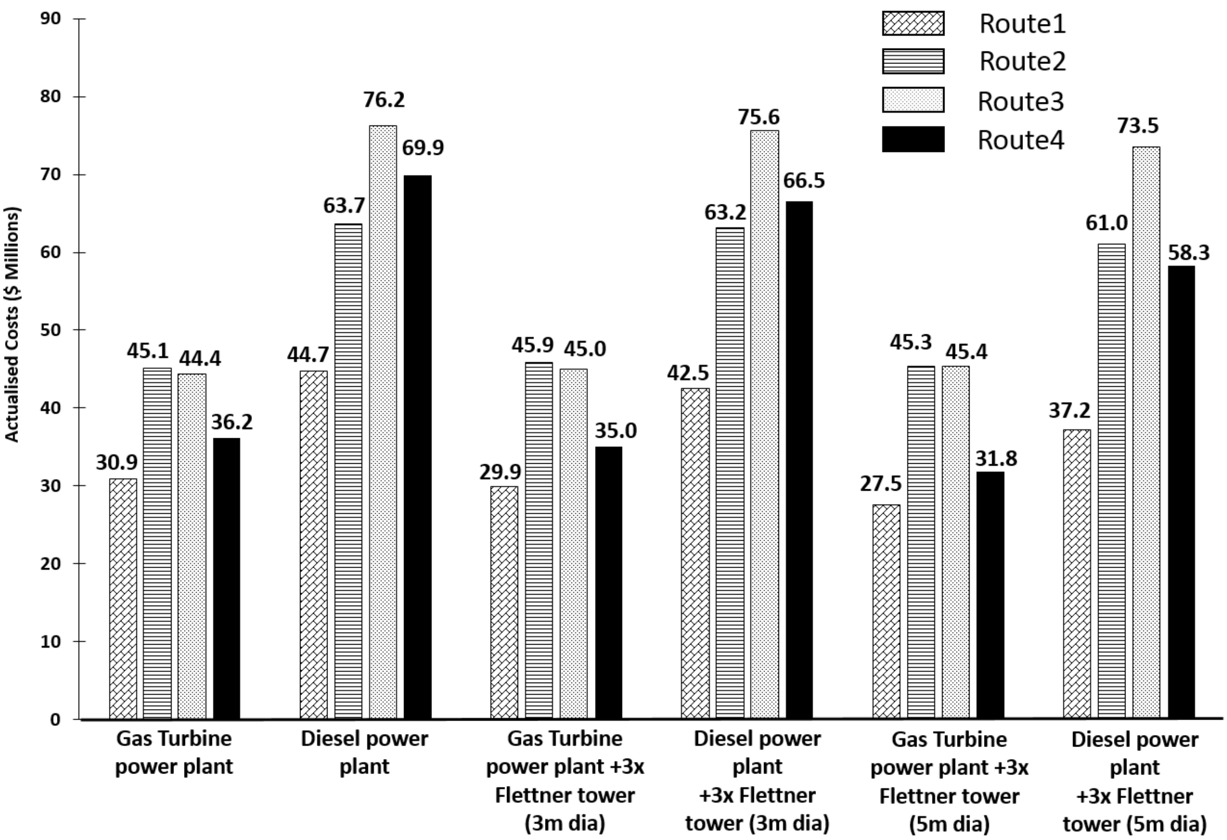


**Figure 14** Actualised costs with the application of the British Columbia tax rates for the analysed configurations

**CONCLUSIONS**

A techno-economic and environmental assessment methodology has been applied in order to assess the performance and economic benefits that may be accrued when utilising conventional propulsion systems in conjunction with Flettner towers. The conventional propulsion systems included gas turbine and diesel engine power plants using Natural gas and MDO as fuels, respectively. The results were found to be promising in terms of environmental benefits and the methodology applied was demonstrated to be useful in technology selection and decision-making process. The work and key results may be summarised as follows:

- Four different international trading routes have been investigated. For a realistic simulation environment, weather models have been used, which provide conditions of the specific geographical region the vessel is operating in. The study clearly indicates that on these specific simulated routes, even if the impact of the implementation of Flettner towers on the vessel emissions and fuel consumption is positive, their economic viability was significantly dependent on the wind conditions and on the dimensions of the towers.
- The study also demonstrated that the wind direction has a larger impact on the performance of the towers than wind speed and, given the assumptions made in the study, the tower with the larger diameter provided a higher propulsive contribution.
- While the simulated routes were assumed to be direct paths and the ship stability issues were not investigated, this study has indicated that the implementation of Flettner towers on commercial vessels could result in up to 20% savings in terms of fuel consumption while further contributing to reduction in $CO_2$ and $NO_x$ emission levels (20% and 25% respectively).
- The economic assessments considered the effects of implementation of environmental emission taxes for $CO_2$ emissions. The assessment indicated that the economic benefits would be dependent on the taxation rates applied on the international shipping for $CO_2$ emissions. Another case study investigated the economic effects of British Columbia environmental legislations, which encourages the use of natural gas instead of diesel oil. Consequent to the lower taxation, the configurations utilising the gas turbine and operated using natural gas were found to be economically more viable than the diesel engine configurations. However, when similar $CO_2$ emission taxation rates were applied to both power plant configurations, it was found that the operational economics was dependent not only on the specific taxation rates applied, but also on the prevailing weather conditions of the simulated routes and the consequent benefits of using Flettner towers harnessing wind power.

To conclude, the analysis developed in this research work indicated how the techno-economic and environmental analysis applied in the marine sector is a very valuable tool to compare and down select amongst several engine configurations.

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# Techno economic and environmental assessment of Flettner rotors for marine propulsion

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