ADAPTATION OF WIND POWER FOR SHIP ESSENTIAL SERVICE SYSTEM ONBOARD

Article history
Received
2 July2016
Received in revised form
5 September 2016
Accepted
25 October 2016

T. K. Kim [a,*], O. Yaakob, [a, b]

[a] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia.
[b] Marine Technology Centre, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia.

*Corresponding author
tankaikim@gmail.com

GRAPHICAL ABSTRACT

ABSTRACT

This study suggests a new approach for the reduction of fuel consumption and CO2 emission with the assist of renewable energy. The focus of the study is the adaptation of wind power electrical generating system onboard. The electricity generated from wind is believed able to help reduce the fuel oil consumption and CO2 emission. A product oil tanker has been selected for the case study. The route of study is the round trip from Singapore to Jeddah and Taichung to Singapore. Wind power generation is calculated based on available of wind data along the routes. Economic assessment has been carried out to assess the feasibility of investment in this project. With the use of simple payback method, the result shows that investment cost will be repaid within 10 years. Besides, Net Present Value indicates a positive value within an investment period of 16 years by 10% internal rate of return. The installation of the system onboard gives a significant reduction in fuel oil consumption and CO2 emission. A 38.69% of saving can be achieved in a year for vessels which travel through the selected routes of study in normal sea going condition.

KEYWORDS

Wind turbine; green energy; FO and CO2 emission reduction

INTRODUCTION

The international shipping industry is a modest contributor to the global carbon dioxide (CO_2) emission. CO_2 is the most significant greenhouse gas (GHG) in term of quantity and contributes to global warming. According to Second IMO GHG Study 2009 done by The International Maritime Organization (IMO), international shipping was estimated to have emitted 2.7 percent of the global man-made emissions of CO_2 in 2007 [1]. Although the emission of CO_2 by international shipping is considered as modest among others, the industry and IMO are putting more effort to control GHG emissions. This is because most of the world trade (90%) is carried through the ocean.

Some methods to reduce GHG emission from shipping industry are by reducing ship fuel consumption, increasing engine efficiency and reducing fuel consumption with the assist of renewable energy. A new chapter entitled "Regulations on energy efficiency for ships" has been added into the MARPOL Annex VI making mandatory to implement Energy Efficiency Design Index (EEDI) for new ships and Ship Energy Efficiency Plan (SEEMP) for all types of ship. This regulation was originally developed as a non-mandatory instrument to help control CO_2 emission from shipping. The regulation was commenced on 1 January 2013 and has a transition period for full application. It is evident that the standard GHG emission for future ship will become stricter.

This study suggests a new approach of reducing fuel consumption and CO_2 emission with the assist of renewable energy. Waves and wind are resources are plenty from the sea. There are numerous researches on the methods to extract energy from waves and wind, with most focusing on using wind to assist in ship propulsion. For this study, the target is to reduce fuel oil consumption by using electricity generated by wind. Hence, vessel shipping routes and wind data had been collected along the year to study the effectiveness of this approach.

Literature Review

Wind-Assisted Ship

Wind-assisted ship is a ship that uses wind as the secondary power source to help propel the ship or to generate electricity. Few centuries ago, ships were initially powered by human energy, followed by the use of soft sail. This happened when people realize the power of the wind and started to utilize it for ship propulsion. Modern inventions and rapid growth of technology of internal combustion engine have led to transformation in ship propulsion method. Majority of ships are now fossil-fuel dependent. The rise of oil price in the 1980s caused a great impact on shipping industry, as most of the cost of shipping comes from fuel oil consumption. As a result, parties in the shipping industry and government have commissioned researches on the use of wind to assist in ship propulsion, with the objective to explore its potential in decreasing fuel oil consumption.

Electrical Power Generation with using Wind Turbine

Wind turbine is a device designed to extract energy from wind. It consists of necessary systems such as the yaw system (for horizontal-axis wind turbine to be always upwind) and electrical generator machine which converts mechanical rotation into electrical power. However, wind energy cannot be captured 100 percent because downstream wind velocity will not be zero in moving air condition. Downstream wind speed zero also means the clog of any flow through the rotor. Hence, only a part of the wind energy will be transferred to the turbine rotors when it rotates. According to Betz law, the maximum energy that can be captured from the total kinetic energy of wind is 16/27 (59.3%). This 59.3% power coefficient is known as Betz limit, and it can only be reached when downstream to upstream wind ratio equals to 1/3. This is only a theoretical value as it is very hard to achieve practically due to many influencing factors, such as wind average velocity, turbine rotational velocity and turbine blade design parameters (e.g.: pitch angle, etc.). To date, the highest power coefficient for optimal modern turbine design can only reach up to 70 to 80% of the Betz limit or Cp = 0.4 [2].

Horizontal- Axis Wind Turbines (HAWT)

Wind turbine is categorized by its blades rotational axis. The design of horizontal-axis wind turbine is more preferable and commonly used in commercial because of its high power coefficient compared to vertical-axis wind turbine. Over the last 50 years, wind turbines developed usually have either 2 or 3 blades. The increase in number of blades will cause an increase in aerodynamic efficiency. Turbine blades must be thinner when the number increases in order to be aerodynamically efficient. Hence, when structural strength is considered, turbine blade cannot be too thin as it has to be strong enough to withstand bending stress induced by axial wind load. In the end, it only yields diminishing return on the aerodynamic efficiency when further increase in the blades number [3].

Vertical-Axis Wind Turbines (VAWT)

Vertical-axis wind turbine is capable of catching wind from all directions. It does not need a yaw mechanism, rudders or downwind coning like horizontal-axis wind turbine. Savonius and Darrieus designs are two distinct types of vertical-axis wind turbine. Darrieus rotor is developed more extensively when compared to Savonius design due to its high power coefficient. Savonius is a drag-type vertical-axis wind turbine; hence it cannot rotate faster than the wind speed, thus this design not suitable for electrical power generation [4]. This study focuses on H blade Darrieus design VAWT. The straight blade design in H rotor can eliminate the problem faced by flex Darrieus rotor. The airfoil blade which is designed to flex in the original blade faces the problem of permanent fatigue on the blade material which may lead to blade failures [5]. Besides, H blade turbine works well in turbulent wind conditions.

The Restriction of the Air Draft of Wind-assisted Ship

Wind turbine equipped in wind-assisted ship, either soft or rigid sails will increase the ship's air draft. This will restrict the routes of travel of the vessel as it may not be able to pass through canals or bridges if the increased air draft exceeds the air draft limitation of the canal or bridge. According to Bøckmann and Steen [9], the bridges that cross the seaward approaches to the world's major ports restrict the air draft of wind assisted ships to about 60 m, unless the wind turbine tower, wing-sails or mast can be folded down. Air draft limitation of Panama Canal is 57.91m, Suez Canal is 68m and Kiel in Germany is 40m [6-8].

Safety Clearance for the Wind Turbine

The clearance around the wind turbine, especially around the blades area, is very important to ensure safety during the operation. The proposed wind turbine is designed to be installed at the front of the ship with a safety clearance of more than half of the breadth of the ship from the blade tips to the superstructure on deck. The safety clearance of blade tips to the freeboard must have a minimum clearance about 3 m, in consideration of human passageway.

Stability of Wind-assisted Propulsion Ship

The heel angle of a 150 m long tanker was found increased, by the horizontal-axis wind turbine having diameter of 39 m and a hub height 39.5 m had shown negligible result, in a research paper published by Eirik Bøckmann and Sverre Steen (2011). According to the result of research, an extreme heeling moment occurred when the ship was sailing at 10 knots with a true wind angle of 104.9˚ with 20 m/s in speed, which caused an apparent beam wind. The calculated heeling moment around the center of gravity of the optimized turbine rig in that research was 6.08 MNm. Heeling moments of 6.08 MNm resulted in a heel angle below 1˚. The increased heel angle can be considered as negligible [9].

Relation between Fuel Saving and CO_2 Emission

The consumption of fuel oil is directly proportional to the CO_2 emission of engine. The fuel oil consumed is multiplied with a non-dimensional factor to calculate the CO_2 emission [10]. While different type of fuel has different value in the non-dimensional factor, C_f. Hence the fuel oil saved by implementing green energy onboard will have a CO_2 emission reduction in the same time with a multiplication factor of C_f.

Research Methodology

Selection of Ship

There are some considerations for the ship selection process. Vessel installed with the wind power system will hinder the use of dockside crane. Increase in air draft due to the height of wind turbine would restrict the vessel from passing through canals and bridge with height lower than its air draft. With these considerations or limitations, selection of types of vessel becomes an important part in the study. Vessels like container ship and bulk carrier are not suitable for installation of wind-assisted power system, while chemical or oil product tanker is more preferable for cargo loading and off-loading, or better transferred through pipelines. Installation of wind power system on product oil tanker will not affect the process of cargo loading and offloading. For this study, a product oil tanker which is still in the preliminary design stage was chosen. Case study on the selected vessel enabled the results obtained to be practicably reasonable.

Ship Particulars

Table 1: Ship particulars of product oil tanker selected

Ship Particulars	Dimensions
LOA	144.60 m
LBP	135.60 m
Breadth mld, B_{mld}	23.00 m
Depth, D	12.50 m
Design Draft, T	8.80 m
Operating Speed, Vs	Abt 12.5 knots
DWT	16,500 tonnes
Propulsion	MAN-B&W 6S42MC-C, 1 set
M.C.R	6480kW @ 136 rpm
SFOC	177g/kWh
Electric generation plant	Main diesel generator sets, 3 set Generator diesel engine: 400 kW @ 1500rpm Alternator: 350 kW, AC400V, 3 Phase, 50 Hz Emergency generator set, 1 set Generator diesel engine: 78 kW @ 1500rpm Alternator: 71 kW, AC400V, 3 Phase, 50 Hz

Selection of Wind Turbine

Vertical-axis wind turbine was selected in this study due to several advantages as listed:

1. capable of catching wind from all directions,
2. can be built lower and more stable since the centre of gravity is low,
3. does not need yaw mechanisms, rudders, or downwind coning,
4. easy to conduct maintenance work because the electrical generator can be put at a lower position,
5. safer operation due to lower rotational speed,
6. has low noise level (low tip speed ratio), and
7. does not suffer much from the constantly varying gravitational loads that normally would limit the size of horizontal- axis wind turbines.

In the end of 2009, Swedish company VerticalWind built a new type of vertical-axis wind turbine with a giromill or H rotor 3 blades design in Falkenberg, named as VW 200. The VW 200 has a direct driven synchronous multipole with permanent magnets generator located at the bottom of the tower. VW 200 has a rated output of 200kW at a rated wind speed of 12 m/s (32 rpm), and it needs a space of 32m in diameter (includes 3m clearance around VW 200) [4]. Hence, only a unit of VW 200 could be used for the wind power generation system due to the limited space available on main deck (see Figure 7).

Particulars of the Selected Wind Turbine

The selected vertical-axis wind turbine is manufactured by VerticalWind AB. The original tower height (40 m) was reduced to 19.5 m due to the standard major port air draft limitation. Besides, the reduced tower height would reduce the added mass onboard and lower the wind turbine's center of gravity, which might affect the ship's stability. Figure 2 shows the power curve of VW 200. The cut-in wind speed for the VW 200 is 4 m/s with a rotational speed of 15rpm, while the rated wind speed is 12 m/s with 32 rpm. The maximum power output can be achieved when wind speed exceeds 12 m/s. Turbine will stop operate when wind speed exceeds 25 m/s. The purpose of setting a cut-off wind speed is to protect the turbine from overloads.

Table 2: The Particulars of the selected vertical-axis wind turbine VW 200 [11]

Description	Detail
Type	Vertical-axis
Model	VW 200
Manufacturer	Vertical Wind AB
Power output	200 kW
Cut-in wind speed	4m/s, (15 rpm)
Rated wind speed	12 m/s, (32 rpm)
Cut-off wind speed	25 m/s
Max wind speed the blades can resist	41.7 m/s, (93 mph)
Tower height	19.5 m
Torque	87 kNm
Number of blades	3
Turbine diameter	26 m
Blade length	24 m
Swept area	624 m^2
Blade chord	1 m
Blade area	58.5 m^2

Figure 1: VerticalWind giromill turbine, VW 200 [4]

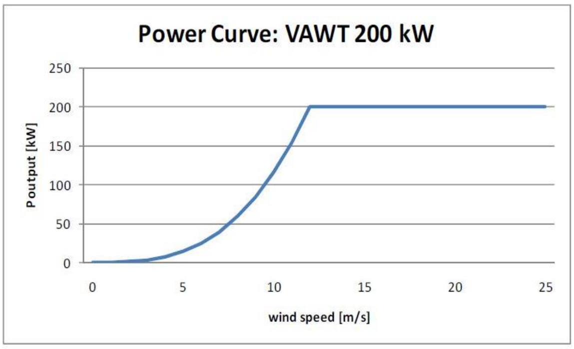


Figure 2: Power curve of the 200kW VAWT of Falkenberg with 3 blades giromill design [4]

Route of Study

Before conducting any test, major oil waterway shipping routes had been studied since product oil tanker was selected. Routes of Singapore to Jeddah and Singapore to Taichung were selected as they have the most active oil shipping activities, and statistical wind data were readily available. The statistical wind data were referred from the daily noon report collected from ships which travel through the routes. The wind data were collected within a period exceeding two years which started from May 2007 until September 2009 [12]. These actual wind data would help in obtaining a close approximation of the wind power that could be generated along the routes.

Routes from Singapore to Jeddah

For analysis, the route from Singapore to Jeddah was divided into 3 sectors, as shown in Table 3 and Figure 3 [12]. The route was divided into sectors to ensure those data collected would be correctly interpreted into useable information in terms of position and wind direction. The same monthly average wind data was used for the route from Singapore to Jeddah and route from Jeddah to Singapore. The assignation of the sectors along the route was fixed to avoid misinterpretation. Ship from Singapore to Jeddah would travel from Sector 1 to Sector 3 while ship which from Jeddah to Singapore would travel from Sector 3 to Sector 1.

Figure 3: Division of route from Singapore to Jeddah [12]

Table 3: Route sectors from Singapore to Jeddah and the estimated voyage day [12]

	Singapore to Jeddah		Estimated Voyage Days
	From	To	
Sector 1	6.3N, 94.2E	5.8N, 83.4E	2
Sector 2	5.8N, 83.4E	14.1N, 62.9E	4
Sector 3	14.1N, 62.9E	12.1N, 46E	3

Routes from Taichung to Singapore

The route from Taichung to Singapore was divided into 2 sectors, as shown in Table 4 and Figure 4 [12]. The same monthly average wind data was used for the route from Singapore to Taichung, Taiwan. The assignation of the sectors along the route was fixed to avoid misinterpretation. Ship from Taichung to Singapore would travel from Sector 1 to Sector 2, while ship from Singapore to Taichung would travel from Sector 2 to Sector 1.

Figure 4: Division of route from Taichung to Singapore [12]

Table 4: Route sectors from Taichung to Singapore and estimated voyage day [12]

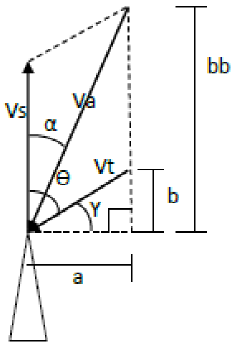
	Singapore to Taichung, Taiwan		Estimated Voyage Days
	From	To	
Sector 1	24.2N, 120.1E	12.1N, 112.6E	3
Sector 2	12.1N, 112.6E	1.0N, 104.5E	2

The Relationship between Wind and Vessel's Motion

Theoretically, wind direction should not affect much on the vertical axis wind turbines performance but it would affect wind velocity [13]. This is because of the chosen wind turbine design was in vertical axis. Hence, the wind turbines would still rotate when a wind comes regardless of the wind direction. This means that the requirement of horizontal axis wind turbine to be always upwind to get a better performance is not an issue for vertical axis wind turbine. However, this is only applicable for vessel which is in stationary condition.

For a moving vessel, the true wind direction will affect the wind turbine performance. This is because the changes in true wind direction to a moving vessel will result in a change in apparent wind speed. Wind which attacks the turbine blades of a moving vessel is apparent wind speed instead of true wind speed. In other words, wind turbine might not operate even if the vessel is moving. This is because attack wind speed will fall below wind turbine cut-in wind speed. Apparent wind is a vector subtraction of wind velocity to the object velocity. It can be obtained through parallelogram method or triangle method. Figure 5 shows the equations derived to obtain apparent wind speed using parallelogram method.

where, Vs = Velocity of Ship,
Vt = Velocity of True Wind,
Va = Velocity of Apparent wind.



$$Y = 90 - \theta$$
$$a = Vt\cos Y$$
$$b = Vt\sin Y$$
$$bb = b + Vs$$
Hence,
$$Va = \sqrt{a^2 + (bb)^2}$$
$$\alpha = tan^{-1}\left(\frac{a}{bb}\right)$$

Figure 5: Apparent wind calculation formula [9]

Electrical Load Analysis

Electrical power required depends on the ship condition. For this study, electrical power for normal seagoing condition was considered because desired wind speed can be obtained in the open sea compared to wind speed at the harbor. Electrical load of ship's essential services system has categories such as engine room machinery, air conditioning unit, refrigeration and ventilation system, workshop device, deck machinery system, galley and laundry appliances, lighting system, communication and navigational system and miscellaneous device. Each equipment or system is classified into continuous loading or intermittent loading. For equipment with continuous loading, electrical load is obtained through the multiplication of rated power with load factor, while electrical load for intermittent loading equipment is obtained through multiplying the rated power and load factor with 0.6 [14]. The summation of the continuous loads and intermittent loads will define the total electrical load for the ship in that particular condition.

For this study, the total electrical load for normal sea going was referred from the available electrical load analysis sheets from the selected vessel. The total electrical load for normal sea going is 250.35 kW.

Arrangement of Wind Turbine Onboard

General arrangement of the selected ship was studied in order to place the wind turbine in the most suitable position. Figure 10 shows the original general arrangement of the ship. Only one unit of wind turbine can be installed onboard the 144.60m long vessel. A clearance distance of 3m was set between the swept areas of maximum deck crane and turbine blades. Meanwhile, the vertical clearance distance between the lowermost turbine blades tips to the passageway of forecastle deck was set to be 3m for safety purpose. The general arrangements of wind turbine installed onboard are shown in Figures 6 and 7.

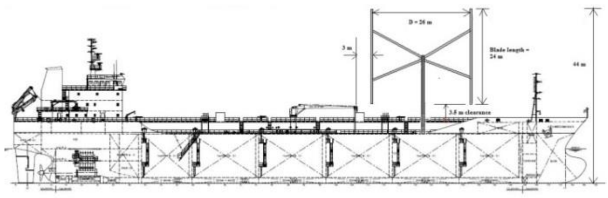


Figure 6: General arrangement of 144.60m product oil tanker with wind turbine

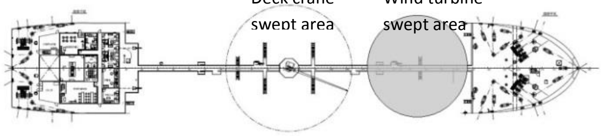


Figure 7: Top view of 144.60m product oil tanker with wind turbine

Ship Stability Assessment

Stability of a ship on water is a major concern in ship design. Stability of ship is defined as the ability of the ship to return in upright position after it is subjected to force caused by wind or waves. The design of a ship must pass all of the IMO ship stability requirements in order to operate safely at sea. IMO states that all ships must have GMt ≥ 0.15m to achieve an initial stability (able to float upright in calm water). In this study, large angle stability analysis was carried out to assess the ship's capability to encounter wind and waves force with its righting arm in any loading condition.

Four loading conditions were selected to assess the ship stability after wind turbine had been installed onboard. The four loading conditions were full load departure, full load arrival, ballast departure and ballast arrival condition. The final results obtained were then referred to the IMO stability criteria. The ship was then confirmed to be stable as it complied with all of requirements.

Maxsurf Modeler and Maxsurf Stability software had been used to obtain the data required to calculate ship stability. A sample drawing of VLCC (Very Large Crude Carriers) in Maxsurf library was selected and scaled down according to the selected ship particulars. The drawing was then exported to Maxsurf Stability. Upright analysis and KN value analysis on the hull form were run in the Maxsurf Stability to obtain the hydrostatic curve and cross curve of the ship.

With known displacement of every loading condition, some important data could be obtained through the hydrostatic curve, which were the ship's draught, KMt, and KB. Meanwhile, the KN value at every heeling angle for the specific loading condition was obtained based on the cross curve of the ship. The steps of ship stability assessment are shown in Figure 8.

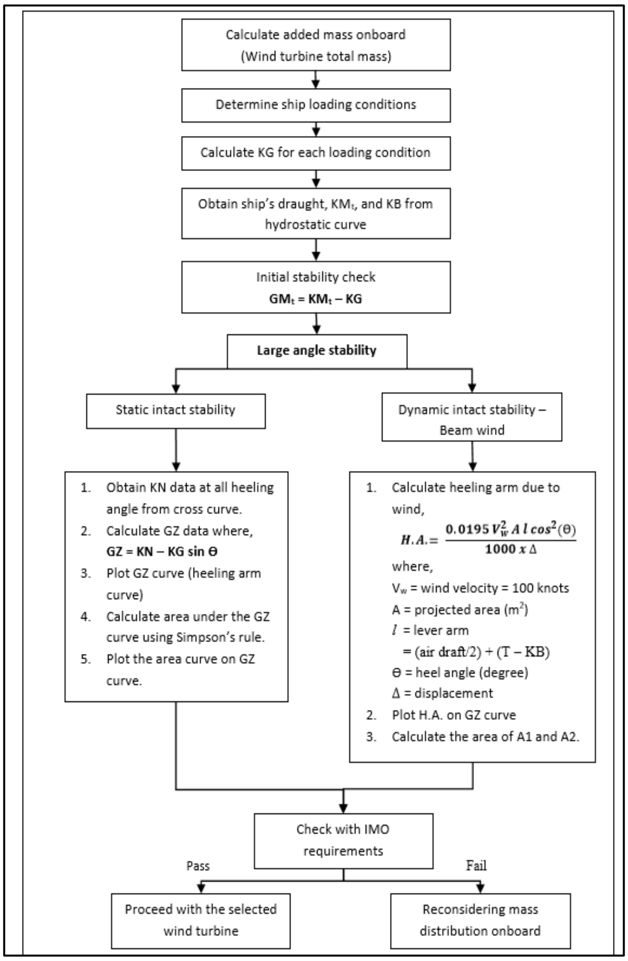


Figure 8: Flow chart of ship stability assessment

Air Drag

Increase in air drag from the wind turbine is put into consideration. In order to evaluate the effect of air drag increment due to wind turbine, the air drag force must be determined. The drag force equation obtained from the Applied Fluid Dynamics Handbook was used [15].

$$F = 0.5\, C\, \rho\, A\, V^2 \quad (1)$$

When the turbine rotates, the air drag force on the vertically rotating turbine blades is regulated by the lift force generated by the blades. It affects the rotating speed of the turbine but does not increase the drag force to the ship. Hence, the drag force is only donated by the tower reference area. The drag coefficient for cylinder, which is the shape of turbine tower, was given as 1.2 [16]. Wind speed of 25 m/s was selected as it is the maximum operating wind speed (cut-off wind speed) of the selected turbine. The reference area for when the turbine would rotate was given as 46.8m2 (3.89% of the ship's original reference area). By using the drag force equation (Eqn. 1), the maximum drag force to be experienced by the ship was estimated to be 21.5 kN when the turbine rotated at its maximum attack wind speed.

When the turbine does not rotate (wind speed below cut-in wind speed or above cut-off wind speed), the turbine blade reference area will contribute to drag force to the ship. The drag coefficient for the airfoil was given as 0.045 [17] and the total turbine blades area was 58.5 m2. The total wind turbine reference area was estimated 105.3 m2, equal to 8.75% of the ship's original total reference area.

The effect to the ship total resistance was considered insignificant as it would increase only 3.89% to 8.75% in the total air resistance, where air resistance would contribute only few percent in the ship total resistance. In ship stability point of view, increase in drag force contributed by the wind when it comes from the other direction will increase the rolling or pitching motion. Since projected sail area is one of the factors in heeling arm due to wind, the effect of increase in air drag was assessed in the part of ship dynamic stability assessments.

Reduction of Fuel Oil Consumption and CO_2 Emission Calculation

Reduction in fuel oil consumption can be calculated when the wind turbine power output is known. Equation 2 below was used to calculate fuel oil saving according to the wind power generated.

$$Fuel\ Oil\ Saved = wind\ power\ generated\ (kW)\ x\ s.f.o.c\ \left(\frac{g}{kWh}\right) \quad (2)$$

The specific fuel oil consumption (s.f.o.c.) of the diesel generator set was referred from the "Marine Propulsion Review in association with MER 2012" magazine published by IMAREST, which was 215 g/kWh.

Reduction in carbon dioxide emission was calculated by using Equation 3. As referred to MARPOL Annex 8, Resolution MEPC.212 (63), the C_f for diesel oil is equal to 3.206 tonne-CO_2 / tonne-fuel. C_f is defined as a non-dimensional conversion factor between fuel consumption measured in grams and CO_2 emission, which is also measured in gram based on carbon content.

$$Reduction\ in\ CO_2\ emission = mass\ of\ fuel\ oil\ saved\ (tonnes) x\ C_f\ \left(\frac{tonne - CO_2}{tonne - fuel}\right) \quad (3)$$

Investment Appraisal Technique

Investment Appraisal is a valuation of the property or investment by the estimate of an authorized person. In order to judge a project or investment, some investment appraisal techniques are used. The results obtained from investment appraisal will give sufficient information to decide on the desirable and the profitability to undertake or invest in that project. Based on the results, information in terms of length of time required to recover the investment cost (Payback Method), actual yearly cost of funds over the term of loan (ARR), the profitability of an investment (NPV) and the internal rate of return (IRR) can be obtained.

For this study, payback method, IRR and Net Present Value method had been selected to calculate the length of time required to recoup the investment cost and to analyze the profitability of this investment. Payback method was performed by summing up the cash inflow and outflow over years and minus by the investment cost. An internal rate of return, i = 10% was selected because it is the minimum desirable rate of return to undertake an investment. Net Present Value of the investment was calculated using [18].

RESULTS AND DISCUSSIONS

Effects of Wind Turbine Installed to Ships Navigation

Increased Extreme Breadth of the Ship

VW 200 has a diameter of 26 m which exceeds the ship breadth (23 m) by 1.5 m at both port and starboard side. It increases the extreme breadth of the ship to 26 m. The horizontal swept area of VW 200 is smaller than the deck crane horizontal swept area; the deck crane is retractable but the wind turbine is not. This would give disadvantages when the ship navigates in a narrow sea way where distance between ships becomes closer.

Increased Air Draft of the Ship

The installation of wind turbine will give an increase in air draft by 7.54 m. The actual air draft of the ship at every loading condition has been determined, as shown in Table 5. The maximum air draft is 39.28m in the ballast arrival condition, passing the standard major port air draft requirements [9].

Table 5: Ship air-draft at different loading condition

Loading Condition	Full Load Departure	Full Load Arrival	Ballast Departure	Ballast Arrival
Air draft (m)	35.18	35.27	39.17	39.28

Propeller Immersion

Immersion of the propeller must comply with the requirements in the vessel loading manual. Propeller immersion less than 100% will cause the loss of vessel performance, over speeding of the main engine, lead to possible stress or damage to machinery. According to MARPOL Annex I, Regulation 13: Segregated ballast tanks, dedicated clean ballast tanks and crude oil washing, Part 2(c) for propeller immersion, the draught must be sufficient for the propeller to be immersed.

As the wind turbine was set to be installed at the front part of the ship, the center of gravity of the ship needed to be shifted to forward. Hence, propeller immersion for 4 loading conditions also needed to be checked. The propeller of the selected product oil tanker had a diameter of 4.1 m, while the height from the keel to propeller uppermost blade tips was 4.713 m. This value was checked with ship draught, and the result showed that it would be fully immersed in these loading conditions.

Table 6: Ship draught in different loading condition

Loading Condition	Full Load Departure	Full Load Arrival	Ballast Departure	Ballast Arrival
Draught, T (m)	8.82	8.73	4.83	4.72

Ship Stability Results

The ship stability result is as shown in Tables 7 to 9. These stability criteria values were obtained as shown in Figure 8. The ship with wind turbine installed onboard complied with all of the IMO ship stability requirements. The most critical loading condition which is ballast arrival condition was selected to undergo the assessment of ship dynamic stability due to beam wind. It was found that there was only 1 degree increment for the maximum heel angle for beam wind at intersection point (c) in ballast arrival condition.

Table 7: Results of Initial stability

Loading Condition	Full Load Departure	Full Load Arrival	Ballast Departure	Ballast Arrival
GMt (m)	3.142	4.141	5.879	6.074

Table 8: Results of ship static stability

No.	IMO Requirement for Static Stability Criteria	Req. Value	With system			
			Full Load Dept.	Full Load Arrival	Ballast Dept.	Ballast Arrival
			Actual	Actual	Actual	Actual
1	Area Under Curve 0-30 deg	>= 0.055 m.rad	0.506	0.503	0.842	0.869
2	Area Under Curve 0-40 deg	>= 0.090 m.rad	0.777	0.781	1.447	1.489
3	Area Under Curve 30-40 deg	>= 0.03 m.rad	0.271	0.278	0.604	0.62
4	Maximum GZ	>= 0.2 m	1.59	1.64	3.61	3.7
5	Angle at Maximum GZ	>= 30 deg	40	42	40	40
6	Initial GM	>= 0.35 m	3.142	4.141	5.879	6.074
			PASS	PASS	PASS	PASS

Table 9: Results of ship dynamic stability due to beam wind

No.	IMO Requirement for Dynamic Stability Criteria	Req. Value	Ballast Arrival			
			Without Wind System		With wind system	
			Actual	Comply	Actual	Comply
1	Max angle of heel at intersection point (c) for beam wind	≤ 10 deg	5 deg	Pass	6 deg	Pass
2	GZ at intersection point (c)	≤ 6/10 of Max GZ	0.56 m	Pass	0.62 m	Pass
3	Area under curve for beam wind	A1 ≥ 1.4 A2	1.4 ≥ 0.94	Pass	1.24 ≥ 0.86	Pass
4	Angle at maximum GZ	≥ 15 deg	40 deg	Pass	40 deg	Pass
			PASS		PASS	

Wind Power Generation

Wind power generation is dependent on the wind speed in the route of travel. The increase of attack wind speed on the turbine blades (apparent wind speed) will increase the power output. The maximum power that can be generated by the selected wind turbine design is 200 kW for wind speed above 12 m/s, and it will not operate at apparent wind speed below cut-in wind speed of 4 m/s, and above cut-off wind speed of 25 m/s, hence giving a zero power output.

Figure 2 presents the data of generated wind power, obtained based on wind turbine power curve projected by monthly average apparent wind speed, Va. As the wind data obtained from Ref. [12] is monthly average true wind speed, the monthly average apparent wind speed was calculated using calculation steps as shown in Figure 5.

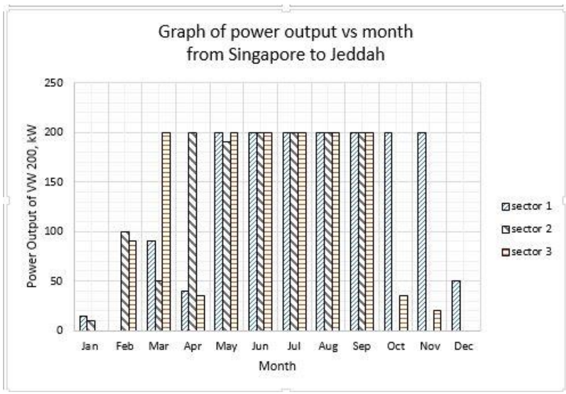


Figure 9: Graph of power output vs month of the route from Singapore to Jeddah

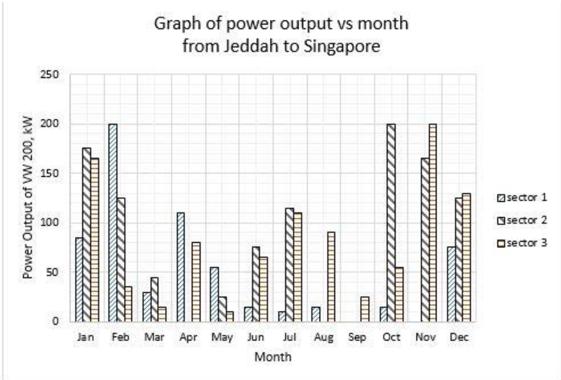


Figure 10: Graph of power output vs month of the route from Jeddah to Singapore

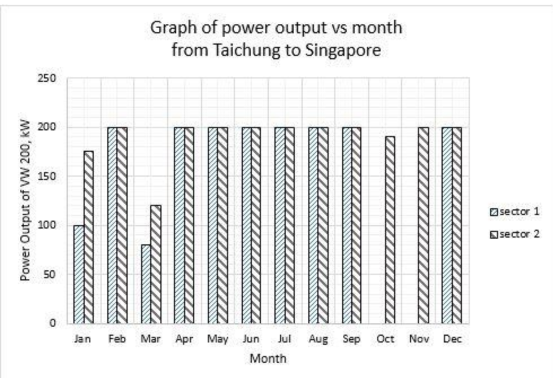


Figure 11: Graph of power output vs month of the route from Taichung to Singapore

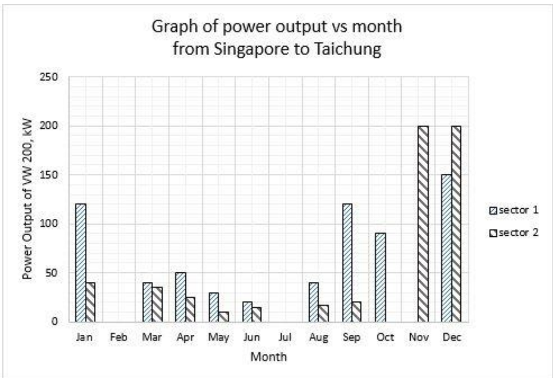


Figure 12: Graph of power output vs month of the route from Singapore to Taichung

Case Study Results on Fuel Oil Consumption and CO_2 Emission Reduction

Case study that is carried out gave a good result of fuel oil consumption reduction and CO_2 emission reduction. Tables 10 and 11 present the methods used to carry out the case study. Power output as listed in Table 10 was obtained using steps as explained in wind power generation section, while other information like route sectors, distance travelled by sectors, voyage duration were obtained from Ref. [12]. Fuel oil (FO) saved per hour was computed using Equation 2 while the reduction of CO_2 emission per trip was computed using Equation 3. Total electrical power required per trip is the product of normal seagoing electrical load and total distance travelled. The percentage of FO saved and CO_2 emission reduction per trip were then used in the case study. Taking an example, the 3rd trip of the case study (Table 11) was in January from Singapore to Taichung. Hence, FO saved for the 3rd trip was referred from the value of FO saved per trip in January in Table 10.

Table 10: Sample calculation of FO and CO_2 reduction per trip (Singapore to Jeddah)

Month	No.	Sector	Vertical Wind AB, VW 200, **power output (kW)**	Distance (km)	Voyage time (Day)	Voyage time (hours)	FO saved per hour (L/hr)	FO saved (L)	Total FO saved per trip (L)	Total FO saved per trip (tonnes)	Reduction of CO2 emission per trip (tonnes)	Electrical load used for normal sea going (kW)	Total electrical power required per trip (kW)	Normal FO used for electrical generation per trip (L)	Percentage of FO and CO2 saved per trip (%)
Jan	1	Sector 1	15	1207.50	2	52.16	3.88	202.20	473.04	0.39	1.261	13059.34	59227.87	15305.28	3.09
	2	Sector 2	10	2426.12	4	104.81	2.58	270.84				26238.95			
	3	Sector 3	0	1842.74	3	79.61	0.00	0.00				19929.58			
Feb	1	Sector 1	0	1207.50	2	52.16	0.00	0.00	4559.84	3.79	12.162	13059.34	59227.87	15305.28	29.79
	2	Sector 2	100	2426.12	4	104.81	25.84	2708.41				26238.95			
	3	Sector 3	90	1842.74	3	79.61	23.26	1851.43				19929.58			
Mar	1	Sector 1	90	1207.50	2	52.16	23.26	1213.20	6681.70	5.56	17.822	13059.34	59227.87	15305.28	43.66
	2	Sector 2	50	2426.12	4	104.81	12.92	1354.20				26238.95			
	3	Sector 3	200	1842.74	3	79.61	51.68	4114.30				19929.58			
Apr	1	Sector 1	40	1207.50	2	52.16	10.34	539.20	6676.01	5.55	17.807	13059.34	59227.87	15305.28	43.62
	2	Sector 2	200	2426.12	4	104.81	51.68	5416.81				26238.95			
	3	Sector 3	35	1842.74	3	79.61	9.04	720.00				19929.58			
May	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	11956.26	9.95	31.892	13059.34	59227.87	15305.28	78.12
	2	Sector 2	190	2426.12	4	104.81	49.10	5145.97				26238.95			
	3	Sector 3	200	1842.74	3	79.61	51.68	4114.30				19929.58			
Jun	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	12227.11	10.17	32.614	13059.34	59227.87	15305.28	79.89
	2	Sector 2	200	2426.12	4	104.81	51.68	5416.81				26238.95			
	3	Sector 3	200	1842.74	3	79.61	51.68	4114.30				19929.58			
Jul	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	12227.11	10.17	32.614	13059.34	59227.87	15305.28	79.89
	2	Sector 2	200	2426.12	4	104.81	51.68	5416.81				26238.95			
Jul	3	Sector 3	200	1842.74	3	79.61	51.68	4114.30				19929.58			
Aug	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	12227.11	10.17	32.614	13059.34	59227.87	15305.28	79.89
	2	Sector 2	200	2426.12	4	104.81	51.68	5416.81				26238.95			
	3	Sector 3	200	1842.74	3	79.61	51.68	4114.30				19929.58			
Sep	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	12227.11	10.17	32.614	13059.34	59227.87	15305.28	79.89
	2	Sector 2	200	2426.12	4	104.81	51.68	5416.81				26238.95			
	3	Sector 3	200	1842.74	3	79.61	51.68	4114.30				19929.58			
Oct	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	3416.00	2.84	9.111	13059.34	59227.87	15305.28	22.32
	2	Sector 2	0	2426.12	4	104.81	0.00	0.00				26238.95			
	3	Sector 3	35	1842.74	3	79.61	9.04	720.00				19929.58			
Nov	1	Sector 1	200	1207.50	2	52.16	51.68	2695.99	3107.42	2.59	8.288	13059.34	59227.87	15305.28	20.30
	2	Sector 2	0	2426.12	4	104.81	0.00	0.00				26238.95			
	3	Sector 3	20	1842.74	3	79.61	5.17	411.43				19929.58			
Dec	1	Sector 1	50	1207.50	2	52.16	12.92	674.00	674.00	0.56	1.797	13059.34	59227.87	15305.28	4.40
	2	Sector 2	0	2426.12	4	104.81	0.00	0.00				26238.95			
	3	Sector 3	0	1842.74	3	79.61	0.00	0.00				19929.58			

Table 11 shows results of the case study in this research. In order to access the effects of wind turbine system to fuel oil and CO_2 emission reduction for the selected vessel (which is still in preliminary design stage), the routes of travel and number of trips travelled by MT Bunga Melati Series [12] in a year were used. From the results obtained, it was found that the wind power generated in that year gave a fuel oil consumption reduction of 107.83 tonnes and CO_2 emission reduction of 345.69 tonnes. The percentage of fuel oil saved and CO_2 emission reduction in a year in normal sea going condition reached 38.69%.

Table 11: Case Study

No.	Month	From	To	Voyage (start)	Voyage (end)	FO saving (L)	FO saving (tonnes)	CO2 reduction (tonnes)	Normal FO used for electrical generation (tonnes)
1	Jan	Singapore	Taichung	1-Jan	9-Jan	2739.01	2.278859	7.3060214	7.1744677
2	Jan	Taichung	Singapore	11-Jan	17-Jan	4751.61	3.953342	12.674414	7.1744677
3	Jan	Singapore	Jeddah	22-Jan	5-Feb	473.04	0.393569	1.2617836	12.733992
4	Feb	Jeddah	Singapore	9-Feb	23-Feb	6801.50	5.658851	18.142278	12.733992
5	Feb	Singapore	Taichung	25-Feb	3-Mar	610.01	0.507528	1.6271358	7.1744677
6	March	Taichung	Singapore	5-Mar	11-Mar	3452.71	2.872656	9.2097339	7.1744677
7	March	Singapore	Jeddah	16-Mar	30-Mar	6681.70	5.559173	17.822708	12.733992
8	Apr	Jeddah	Singapore	3-Apr	17-Apr	3128.52	2.602925	8.3449769	12.733992
9	Apr	Singapore	Taichung	19-Apr	25-Apr	1286.50	1.070365	3.431591	7.1744677
10	Apr	Taichung	Singapore	27-Apr	3-May	6888.88	5.73155	18.375349	7.1744677
11	May	Singapore	Jeddah	8-May	22-May	11956.26	9.947612	31.892044	12.733992
12	May	Jeddah	Singapore	25-May	8-Jun	2439.22	2.029431	6.5063559	12.733992
13	Jun	Singapore	Taichung	10-Jun	16-Jun	601.74	0.500651	1.6050857	7.1744677
14	Jun	Taichung	Singapore	18-Jun	24-Jun	6888.88	5.73155	18.375349	7.1744677
15	July	Singapore	Jeddah	29-Jun	13-Jul	12227.11	10.17295	32.614482	12.733992
16	July	Jeddah	Singapore	17-Jul	31-Jul	5512.33	4.58626	14.703549	12.733992
17	Aug	Singapore	Taichung	2-Aug	8-Aug	976.91	0.81279	2.6058033	7.1744677
18	Aug	Taichung	Singapore	10-Aug	16-Aug	6888.88	5.73155	18.375349	7.1744677
19	Aug	Singapore	Jeddah	21-Aug	4-Sep	12227.11	10.17295	32.614482	12.733992
20	Sept	Jeddah	Singapore	8-Sep	22-Sep	514.29	0.427887	1.3718056	12.733992
21	Sept	Singapore	Taichung	24-Sep	30-Sep	2390.43	1.988841	6.3762243	7.1744677
22	Oct	Taichung	Singapore	2-Oct	8-Oct	3311.50	2.755169	8.8330721	7.1744677
23	Oct	Singapore	Jeddah	13-Oct	27-Oct	3416.00	2.842108	9.1117986	12.733992
24	Nov	Jeddah	Singapore	31-Oct	14-Nov	8583.17	7.141197	22.894677	12.733992
25	Nov	Singapore	Taichung	16-Nov	22-Nov	3485.79	2.900178	9.2979706	7.1744677
26	Nov	Taichung	Singapore	24-Nov	30-Nov	3485.79	2.900178	9.2979706	7.1744677
27	Dec	Singapore	Jeddah	5-Dec	19-Dec	674.00	0.560767	1.7978177	12.733992
28	Dec	Jeddah	Singapore	23-Dec	6-Jan	7205.60	5.995059	19.22016	12.733992
						129598.50	107.83	345.69	278.71844

Techno-economic Analysis

Techno-economic analysis was conducted to predict the returns of this investment. Fuel oil saved was treated as the cash inflow unit, while installation cost, maintenance and service cost were the cash outflow unit. Table 12 shows the summary of the overall cost needed to invest in this proposed project. The data in this table had been used in the calculation of payback and Net Present Value of this investment.

Table 12: Summary of the cost detail

Description	Value
Wind turbine cost estimation	800,000 USD
Installation cost (5% of the system)	40,000 USD
Service and maintenance cost (7% of the system)	56,000 USD
Total FO saved per year	107.83 tonnes
	99,790.80 USD
Diesel oil price	0.77 USD/ liter
Fuel price yearly increment	10%
Service cost yearly increment	5%

Simple Payback Method

Simple payback method showed that the investment would give a positive return in the 10th year. The major drawback of using this simple payback method is that it does not account for the time value of money (TVM).

Net Present Value (NPV) and Internal Rate of Return (IRR)

A minimum desirable rate of return (i = 10%) was chosen to calculate the NPV of the investment. The present value of each cash inflow and outflow was calculated by multiplication with the present worth factor obtained from compound interest table. The investment was predicted to have a positive NPV in the 16th year with the minimum desirable rate of return.

Conclusion and Recommendations

In conclusion, this study has shown that the suggested method can promote the reduction of fuel oil consumption and CO_2 emission by 38.69% for electrical generation in normal sea going condition. The main objective of this study has been achieved, as there is a significant reduction in fuel oil consumption and CO_2 emission. The effectiveness of the wind power system in fuel oil and CO_2 emission reduction is, however, highly dependent on the wind condition along the route that the ship travels. Different route with different wind condition will give different wind power output.

The ship with wind turbine installed onboard complies with all of the ship stability criteria set by IMO. This shows that the ship is stable even after the system installed onboard. Techno-economic assessment has been done, which gives an estimate period of return to the investment with the minimum rate of return. It is estimated to take 16 years to have a positive NPV in order to recover the investment cost of installing such a system onboard. With the information provided in this research study, the feasibility to invest by implementing this suggested method has to be judged by the investor.

For future researches, there are some aspects that need to be considered to further improve this wind power generating system, such as recommended below:

1. Proposal to design a hybrid power generating system to make the suggested wind power system practically applicable.

2. To strengthen the turbine blade by modification to meet marine grade. The current wind turbine design is only capable to operate in the onshore wind farm. Hence, its blade strength can only withstand up to 41.7m/s wind speed. In order to operate in offshore condition, the strength of the turbine blade needs to be increased to be able to survive in the rough sea.

3. To utilize smaller power diesel generator sets. When there is enough wind power generated, some diesel generator sets can be shut down, to reduce more CO_2 emission.

REFERENCES

[1] *IMO, Second IMO GHG Study 2009. 2009: The International Maritime Organization (IMO).*

[2] *William Shepherd, L.Z., Electricity Generation using Wind Power. 2011, Singapore: World Scientific. 241.*

[3] *Hau, E., 2006. Wind turbine Fundamentals, Technologies, Applications. Economics 2nd Edition. Springer.*

[4] *Marco D'Ambrosio, M.M., 2010. Vertical Axis Wind Turbines: History, Technology and Applications, in Energy Engineering. May 2010, Halmstad University, Sweden. p. 91.*

[5] *Ragheb, M. July 2014. Vertical Axis Wind Turbines.*

[6] *Wikipedia. Panama Canal 14th March 2015].*

[7] *Wikipedia. Suezmax. 14th March 2015].*

[8] *(UAC), U.C.A.G. General Information about Kiel-Canal Transits. 14th March 2015]; Available from: www.kiel-canal.de/bilder/pdf_files/max_dimensions_kiel_canal_072005.pdf.*

[9] *Bøckmann, E. & Steen, S., June 2011. Wind Turbine Propulsion of Ships, in Second International Symposium on Marine Propulsors, Hamburg, Germany. p. 10.*

[10] *II, M.A.,2011. Adoption of The International Code on Intact Stability.*

[11] *Engström, S., August 2010. Trends and development in wind power technology.*

[12] *Harun, H.B., December 2011. Wind Assisted Propulsion System for Fuel Saving, in Faculty of Mechanical Engineering (Marine Technology). Universiti Teknologi Malaysia.*

[13] *Dabiri, J.O., 2012. Potential order-of-magnitude enhancement of wind farm power density via counter - rotating vertical-axis wind turbine arrays. Journal of Renewable and Sustainable Energy. 3: 043104.*

[14] *Boyle, G., 2007. Renewable Electricity and the Grid: The Challenge of Variability. Earthscan, UK.*

[15] *Belvins, R.D., 2003. Applied Fluid Dynamics Handbook. Krieger Publishing Co.*

[16] *Kundu, P.K., 2001. Fluid Mechanics. 2nd ed. 2001: Academic Press (An imprint of Elsevier Science).*

[17] *Administration, N.N.A.a.S. Shape Effects on Drag. 24th March 2015]; Available from: www.grc.nasa.gov/WWW/k-12/rocket/shaped.html.*

[18] *White, J.A., 2010. Principles of Engineering Economic Analysis. 5th Edition edition: John Wiley & Sons. Inc.*