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MONTEREY, CALIFORNIA

THESIS

COST BENEFIT ANALYSIS OF THE INSTALLATION OF
A WIND TURBINE ON A NAVAL SHIP

by

Dimitrios Tsaknias

September 2010

Thesis Advisor: Fotis Papoulias
Second Reader: Kostantinos Rados

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13. ABSTRACT (maximum 200 words)

In order to reduce environmental pollution, reduce dependability from foreign energy sources, and avoid the uncertainty associated with an unpredictable rise in the price of oil, the use of alternative forms of energy is in worldwide demand. A popular and rapidly developing alternative form of energy is wind energy. The use of wind energy on a naval ship is the subject of this thesis. A preliminary feasibility study has been undertaken in order to evaluate wind energy potential and drawbacks.

As expected, installation of a wind turbine on a ship must meet several conflicting requirements and is subject to environmental uncertainties. Such uncertainties are in turn coupled with the geographic area of operations of the ship, which makes the problem highly dependent on the overall operational concept and mission of the ship. A coupled ocean/atmosphere mesoscale prediction software (COAMPS) developed by the Naval Research Laboratory is used in order to obtain realistic wind profiles. During this study, the vital electrical circuit elements of the hybrid system are analyzed along with their performance and restrictions of their use. The operational requirements of the ship are taken into account with regards to tower and turbine sizing and its position on the ship as well as all relevant naval architecture characteristics of the ship after installation. A hybrid system is designed and analyzed to cope with the uncertainty associated with wind power. Finally, an economic evaluation of the hybrid system is performed, in order to evaluate if and under what circumstances the use of the hybrid system is a profitable investment.

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**COST BENEFIT ANALYSIS OF THE INSTALLATION OF
A WIND TURBINE ON A NAVAL SHIP**

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Lieutenant Grade, Hellenic Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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and

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Daily autonomy
AKWh	Annual energy production [kWh/year]
AOM	Annual operation and maintenance cost [$/year]
B	Overall width [m]
BM	Metacentric radius [m]
C_{AH}	Amp-hour capacity
C_{batt}	Battery bank cost [$]
C_{be}	Cost of battery erosion [$/KWh]
C_{bw}	Battery cycling cost [$]
C_f	Cost of fuel [$/liter]
C_S	System installed capital cost [$]
C_{Wh}	Watt-hour capacity
CFD	Computational fluid dynamics
COE	Cost of energy [$/KW]
D	Displacement [tons]
d	Discount rate
DOD	Depth of discharge
E	Fuel costs yearly [$]
E_{bat}	Battery stored energy [KWh]
E_{batt}	Battery energy capacity [KWh]
E_{dg}	Diesel engine generated energy [KWh]
E_{kin}	Wind kinetic energy
E_l	Load demand energy [KWh]
E_{wtg}	Wind turbine generated energy[KWh]
EODV	End of discharge voltage
ESR	Equivalent series resistance [Ωhm]
F_o	Diesel no-load fuel consumption [liters/hr]
FCR	Fixed charge rate per year
FV	Future value [$]

GM	Metacentric height [m]
GRI	Graphical results interface
GUI	Graphical user interface
i	Inflation rate
IC	Initial cost of installation [$]
KB	Vertical center of buoyancy [m]
KG	Ship vertical center of gravity [m]
KG_{TOWER}	Tower vertical center of gravity [m]
KG_W	Wind turbine vertical center of gravity [m]
KM	Vertical metacentric height [m]
L	Overall length [m]
LBP	Length between perpendicular [m]
LC	Critical load [KW]
Ltyp	Number of cycles at the typical depth-of-discharge
LCB	Longitudinal center of buoyancy [m]
LCC	Life cycle cost [$]
LCG	Ship longitudinal center of gravity [m]
LCGW	Wind turbine longitudinal center of gravity [m]
LRC	Levelized replacement cost [$]
M	Overall operation and maintenance costs yearly [$]
m	Mass of air [Kgr]
MPV	Mid-point voltage
nbat	Battery round trip efficiency
ninv	Inverter efficiency
nwh	Battery bank efficiency
NPV	Net present value [$]
P	Wind power [Watt]
p	Air density [Kg/m3]
Pd	Diesel operating power [KW]
pi	Nominal interest
Pl	Inverter total power loss [KW]
Po	Inverter output power [KW]

Pr(n)	Yearly profit of the system [$]
PTO	Diesel-rated power [KW]
PV	Present value [$]
Q	Fuel consumption [liter/h]
R	Replacement costs yearly [$]
r	Internal rate of return
ri	Real interest
RPM	Revolutions per minute
S	Salvage value [$]
SP	Payback time [years]
t	Trim [m]
TA	Depth at backward perpendicular [m]
TF	Depth at forward perpendicular [m]
TM	Mean draft [m]
V	Speed of air [m/sec]
VRLA	Valve regulated lead acid battery
WTOWER	Tower weight [tons]
WTURBINE	Wind turbine weight [tons]
XL	Levelized annual cost [$]
Xtyp	Typical depth of discharge

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I.   INTRODUCTION

A.   MOTIVATION

The continual and unpredictable rise in the price of oil revived the demand for use of alternative forms of energy to produce energy. One attractive and environmentally friendly renewable form of energy is wind.

In contrast to fossil fuels, wind can be found everywhere across the world. It is sustainable, free, and abundant. However, wind has low density and varies a lot from area to area. Because of the need to capture large areas and the storage of backup power, the initial costs are higher.

The shipping industry has been significantly affected by the world oil price. Furthermore, the current environmental awareness makes it urgent to reduce the consumption of fossil fuel. There is major interest on how to reduce costs and pollution by using wind as a power source for ships. This power source can provide ship propulsion and can cover electrical supply requirements. There are many different methods and ideas for wind propulsion with different outcomes. The most known techniques are the Flettner, the kite, the wing profile, and the wind turbine [1]. Wind turbines are currently used for small applications on ships.

In this study, the use of a wind turbine is examined only for electrical supplies under certain circumstances. These are specified below.

B.   OBJECTIVES

The primary goal of a warship is to perform the required missions with success during peace or during war. To achieve this, a number of functions must be properly performed. The use of the wind turbine on the ship should not prevent, cancel, or delay these functions.

The installation of a wind turbine on the ship means extra weight and forces. If the ship travels while using the wind turbine, extra resistance would be generated on the ship by the wind. Extra engine power would be required to maintain the same speed as

without the use of the wind turbine. In this case, however, the specific fuel consumption would be increased and would probably lead to an unprofitable solution for the installation of the wind turbine.

The stability of the ship is also considered to be a problem. This is because the mounted system of the wind turbine would create a heeling moment. This heeling moment is more easily and safely controlled when the ship does not travel. In this case, the stability of the ship can be managed by moving water from the balanced tanks. The mounted system should also be movable and, when the ship is about to travel, it should easily be inactivated.

Since using the wind turbine when the ship travels is a complicated, dangerous, and probably not profitable, it is excluded in this study. This thesis focuses on analyzing when the ship is away from its naval base and does not travel. Currently, in this case, the electricity supply is provided by diesel engines with fuel consumption. Instead of utilizing the diesel engines, the objective of this study is to examine how and under what circumstances is it profitable to utilize a wind turbine on a naval ship when the ship is away from its naval base and does not travel.

Additionally, it is well understood that the power output of a wind turbine is a strong function of the wind velocity. Therefore, a reliable wind forecast methodology needs to be incorporated into the study. Since such a forecast is highly dependent on the geographical area of operations, a realistic operational profile of the ship must be included. Fusing all of these items into a comprehensive design methodology is the primary objective of this work.

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C. POSITION OF WIND TURBINE ON THE SHIP

The most critical factor for a wind turbine is the annual energy production from the wind turbine. This depends mainly on the specific area that the wind turbine is going to operate. Since this study is for the installation of a wind turbine on a ship, this area is the environment that the ship is going to perform its mission. This area is known in advance and, according to data from meteorological stations, wind power potential and expected energy production can be predicted.

This calculated energy production for the specific environmental area may differ from the energy production of the wind turbine. Since the wind turbine is placed on the ship and close to the load, local parameters would influence its performance. It is clear that a location of the wind turbine in an exposed terrain is preferred. This is because the wind turbine speed would not be lowered by obstacles that the blades of the wind turbine would encounter. Thus, a wind turbine should be located above and away from obstructions.

At this point, the question is: Is there a preferred position on a ship to place a wind turbine? Since it must be exposed to the wind, it should be mounted at the upper deck and in an open terrain. A known, rigid, and conceivable mounting area is the fore deck with capstan and anchor mounting point. In this area, the related wind turbine mechanism should be mounted away from the mooring deck [1].

The bow is the part of the fore deck that is more interesting to mount a wind system. This is due to its characteristic shape. To predict the appropriate position of installation, a computational fluids analysis CFD should be performed. The ship and bow can be simulated to approximate how the wind behaves. According, to the results, the magnification of the wind speed and the point of separation are revealed. Separation occurs about 50 degrees of the bow [1]. Separation and turbulence, however, increase the total drag of the ship and decrease the power energy outcome of the wind turbine. Thus, for the system to be more effective, it should be positioned away from and before the separation point.

In summary, a wind turbine should be installed at the upper deck at the bow, before and as far away as possible from the separation point.

D. LOAD CHARACTERISTICS

The purpose of this thesis is to investigate the case when the ship is away from its naval base and does not travel. The energy production of the wind turbine would only be to cover the ship's electrical needs and not for its propulsion requirements. Therefore, the load demand of the ship would be restricted and could be modeled as constant. A minimum number of electrical and electronic devices would be operated. As the load needs are known and well specified (fire pump, water pump, electrical heaters, etc.), this would easily be accomplished. Specifically in this study, the load is considered to be constant, and equals 25 KW, according to recorded technical data.

E. STUDIED SHIP

For the purpose of this study, the ship would be a NATO class gunboat. The general characteristics of the ship and a figure are shown in Table 1 and Figure 1.

Displacement, D (tons)	515
Overall length, L (m)	55
Overall width, B (m)	10.5
Mean draft, T_M (m)	2.54
Speed (knots)	25
Propulsion	2 MTU 16V 1163 TB63 diesels 10,000 HP (7.3MW) sustained, 2 shafts, Kamewa-controlled pitch propulsion
Electrical supply	4 diesel engines KOHLER 40 EFOZC, 240/415 V, 50 HZ, 3 phase, 40 KW
Crew	36 plus 25 troops
Range (Nm) at 25 knots	500

Table 1.　　The general characteristics of the ship.

Figure 1.   NATO Finnish class gunboat. From [2]

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II.   WIND TURBINE

A.   MAIN PARTS OF A WIND TURBINE

There are four main parts of a wind turbine: the blades, tower, nacelle, and base. The blades are designed like airplane wings and are used to capture the wind's energy. They spin at a slow rate of about 20 revolutions per minute (RPM). The tower contains the electrical conduits; provides access to the nacelle for maintenance; and supports it. The nacelle houses a generator and gearbox. Finally, the base supports the whole structure and is made of concrete and steel [3] (Figure 2).
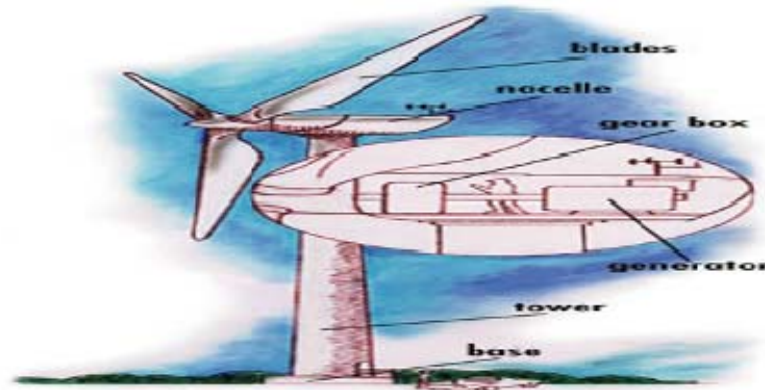
Figure 2.   The main parts of the wind turbine. From [3]

B.   POWER AND ENERGY PRODUCED

In general, the energy contained in the wind is its kinetic energy (E_{kin}) and the equation is:

$$E_{kin} = \frac{1}{2}MV^2 \tag{1}$$

where:

V = the speed of air (m/sec),

m = the mass of air (kgr).

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The power (P) in the wind in watts for a mass of air flowing through a certain area (A) is equal to:

$$P = \frac{1}{2} pAV^3 \qquad \qquad (2)$$

where:

p = the density of air (kg/m^3).

To estimate the power output of a wind turbine, however, its characteristic wind speed power curve and speed frequency distribution at the site where the wind turbine would be placed must be known. The shape of the power curve depends on blade area, number of blades, blade shape, choice of airfoil, speed of rotation, cut-in wind speed, rated speed, and gearing and generator efficiencies. A typical wind turbine power curve is demonstrated in Figure 3.
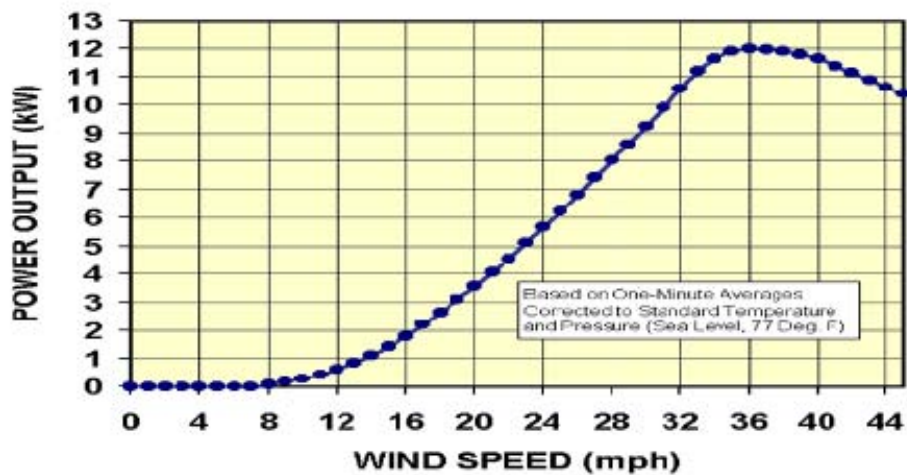
Figure 3.   A typical power curve of a wind turbine. From [4]

The wind speed frequency distribution is a graph showing the number of hours for which the wind speed blows at different wind speeds during a given period of time. To find the energy produced at a specific wind speed, we must multiply the corresponding turbine power for this wind speed given by the turbine's power curve by the number of

hours of its duration. Finally, the total energy produced is calculated by the summation of the energy produced at all the wind speeds within the operating range of the turbine.

C.   TYPES OF WIND TURBINE

1.   Horizontal Axis Wind Turbines

The horizontal-axis wind turbines have the main rotor shaft and the electrical generator at the top of a tower and must be pointed into the wind. They usually have a gearbox, which turns the slow rotation of the blades into a quicker rotation to drive an electrical generator (Figure 4).

Their most important advantage is the variable blade pitch. This gives the turbine the ability to collect the maximum amount of wind energy for the time of day and season. They are also highly efficient. Also, because their blades move perpendicularly to the wind, there is reduced vibration and noise at the coupling at the tower or mount. The main disadvantages include: the additional yaw control mechanism is needed to turn the blades and nacelle toward the wind; fatigue and structural failure of downwind designs; difficulties and high cost in transportation and installation of high towers; and reflections of tall turbines may affect side lobes of radar installations [5].

Figure 4.   The horizontal axis wind turbine. From [6]

2.   Vertical Axis Wind Turbines

The vertical axis wind turbine has the main rotor arranged vertically and the turbine does not need to be pointed into the wind to be effective (Figure 5). It this case, the generator and the gearbox are usually placed near the ground.

The major advantages include: no need for a massive tower structure and yaw control mechanism; ease of maintaining the generator (it is located nearer the ground); lower noise signature; lower wind start up speeds; and it does not have to face the wind's direction to be effective.

Drawbacks are: increased possibility of blade failure by fatigue; less energy output at a given site than a horizontal wind turbine with the same footprint or height (rotors are located near the ground where wind speeds are lower due to the ground's surface drag), generation of pulsating torques; and high vibrations, noise, and maintenance [5]. For a ship application, a horizontal axis wind turbine is preferred since it gives more energy output, generates less noise and requires less maintenance.

Figure 5.   The vertical axis wind turbine. From [7]

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D.   CHOICE OF THE TOWER

In general, wind is slowed down by frictional contact with the ground, especially by trees, buildings, or other rough surfaces. Therefore, the higher a turbine can be mounted, the more power it will generate since the power product is proportional to the cube of the wind speed. This is the reason why wind turbines should be mounted as high as possible.

There are three types of towers available on the market: the guyed tower, the freestanding tower, and the hydraulic tower. The guyed tower has four guy wires tensioning the tower from a point about halfway up to four points in the ground. The freestanding tower is a substantial steel column, which takes up less ground area, but requires a larger and stronger central foundation. Finally, the hydraulic tower is a tower with the ability to lower and raise the wind turbine generator by using the hydraulic system. It requires less space than the guyed tower and delivers lower visual impact. Also, there is no need for a crane which reduces installation and maintenance costs [8].

Due to operational restrictions, the wind turbine must not stand up when the ship travels. The height of the tower should be as short as possible, satisfying the required power output of the wind turbine, so that it could be lay down on the available area of the front main deck. Also, the procedure of lowering and standing the tower should be as easy as possible. There must also be minimum risk to the ship's crew. Therefore, the best solution, in this case, is a hydraulic electric tower. The technical data and the image for the proper hydraulic tower are specified in Table 2 and Figure 6.

Height (m)	8
Bottom diameter (mm)	360
Bottom flange diameter (mm)	600
Thickness (mm)	6
Weight (Kg)	900

Table 2.   The technical specifications of the hydraulic tower

Figure 6.   The 8m electric hydraulic tower. From [8]

E.   CHOICE OF THE WIND TURBINE

The hydraulic electric tower is the best solution for the installation of a wind turbine on a ship. The manufacturing company suggests that a wind turbine with auto-furl control for rotor over speed protection is strongly recommended for this tower. Furling describes the action of the tail boom pivoting around to be at right angles to the axis of rotation. This action turns the blades out of the wind and, thereby, reduces power output. A wind turbine with auto-furling ability is the Westwind 10 kW wind turbine.

This is a new technology horizontal axis wind turbine, almost silent in operation with less vibration. It can be connected to the electricity grid directly or remain completely independent, drawing their energy requirement from their own storage bank of batteries. It consists of three blades, up wind of the tower on a horizontal axis, and attached directly to a sealed permanent magnet generator. It is direct drive with no gearbox, resulting in more power production and low maintenance over designs using gearboxes. Its permanent magnet generator combines high efficiency with simplicity. This generator is also sealed to stop the ingress of foreign particles. This reduces corrosion and stops the magnets from attracting airborne particles. Corrosion is also

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reduced since all steel components are hot dip galvanized during manufacture [9]. The wind turbine selected image and technical data are represented in Figure 7 and Table 3.

Figure 7. **The Westwind 10 kW horizontal wind turbine. From [9]**

Rated power	10 kW
Rated wind speed	14 m/sec
Start-up wind speed	2 m/sec
Cut-in wind speed	3 m/sec
Furling wind speed	16 m/sec
Rotor diameter	6.2 m
Rotor speed	110-600 rpm
Blade material	Pultruded fibreglass
Weight	380 kg
Over speed protection	Auto tail furl
Generator (direct drive)	26 pole NeFeB
DC charge voltages	110,120 V
DC charge controller	PWM shunt regulator

Table 3. **The technical specifications of the wind turbine**

F.   CONTROL OF THE WIND TURBINE

1.   Methods of Control of Wind Turbine

A wind turbine is a revolving machine that converts the kinetic energy from the wind into mechanical energy. This mechanical energy is then converted into electricity that is sent to a power grid. The turbine components responsible for these energy conversions are the rotor and the generator.

The power output of a wind turbine, in many cases, should be optimized or limited. The control of a turbine can be obtained by controlling the generator speed, blade angle adjustment, and rotation of the entire wind turbine. There is also a stall regulation, but it is uncontrolled and not worthy in use. Blade angle adjustment and turbine rotation are also known as pitch and yaw control [10].

In most cases, the wind turbine is directly connected to the grid with constant speed. The wind speed fluctuations cause relatively high loads to the wind turbine. With blade pitch control, an optimum blade angle is maintained to achieve certain rotor speeds or power output. In the case of a fixed wind turbine, the ability of power limiting depends on rotational speed, wind speed, and blade profile. In general, pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speeds. It requires pitch mechanisms and actuators. It allows the set up of a start up pitch angle for easier start up of the wind turbine in low wind speed. It also allows the set up of the running angle when the turbine has the necessary operating speed. It is rather complicated and expensive, however, compared with other power-limiting methods.

In contrast, yaw control is more controllable and does not require pitch mechanisms. It steers the turbine into the wind for starting and out of the wind for shut down.

In the case of constant speed, there is only one wind velocity that results in an optimum tip speed ratio. The wind turbine does not extract the maximum power from the wind. Thus, it requires looking into variable turbine speed. In this case, there is the ability to operate the wind turbine constantly near to its optimum tip-speed ratio and to control

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the rotor speed. This results in the following advantages: (a) increase in the annual production of energy; (b) reduction of the mechanical stresses due to compliance to the power train and, therefore, the increase of life; (c) output power variation is decoupled from the instantaneous condition present in the wind and mechanical systems; (d) reduction of the acoustic noises; (e) improvement of the power quality by reduction of the power pulsations; (f) reduction of the complexity of pitch control since the pitch control time constant can be longer. The major drawback of the variable speed configuration is the complexity and the additional cost. This is because more components must be used. Finally, the control is based on an algorithm, where the electrical torque is proportional to the square of the rotational speed. The blade pitch is activated when the speed of the turbine is higher than a rated speed. It keeps the torque at the rated value and keeps the speed below the maximum value. A yaw control system can also be used with increased stress on the mechanical system in this case [10].

2.   Control Objectives

In general, wind turbines are designed to operate up to a maximum (or cut-up) speed and should be shut down above this wind speed. Also, at very low wind speed, there is very little energy to be extracted. It should not be forgotten that wind turbines consume energy (control systems, actuators, etc.), so a start up (or cut-in) wind speed should be defined below which the wind turbine is shut down.

Consequently, the wind turbine operates between a cut-in and a cut-out wind speed. These regions are also mentioned as below-rated and above-rated wind speed. The term rated means the wind speed at which the wind turbine generates its maximum power output. Therefore, there are four regions for the operation of the wind turbine against the wind speed [11]:

a) Below cut-in wind speed: at this region, the wind turbine is shut down due to less wind power.

b) Below-rated wind speed: at this region there is less power available than the rating of the governor.

c) Above-rated wind turbine: at this region there is more power available than the rating of the governor.

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d) Above cut-out wind speed: at this region there is more energy available than can be absorbed with safety by the load. Thus, the wind turbine is shut down.

The output of a wind turbine depends on the wind speed and, therefore, the region of the operation. It also depends on if the wind turbine has constant or variable rotor speed. With variable rotor speed with the wind speed, maximum power can be generated. The problem with the operation of a wind turbine is how to use the extra energy above-rated wind speeds. In this case, the use of stall, pitch, or yaw regulation is necessary. For stall regulation, the power output is limited by the initial setting of the rotor blades. For pitch regulation, the variable rotor blades pitch angle maintains constant power output. Finally, at yaw regulation, the misalignment between the wind turbine and the wind direction maintain a constant power output.

At the region below cut-in wind speed, the wind turbine is shut down by activating the brake. When the wind speed reaches the running speed again, the brake releases and a start up pitch angle for easier starting is set up with zero load. Then a running angle is set when the turbine has the necessary operating speed.

At the region below-rated wind speed, there can be maximum power output with variable speed rotor. This is because the generator load is varied to maintain an optimum tip speed ratio. A dump load can also be used for this reason.

Finally, at the region above cut-out wind speed, the wind turbine stops by gradually pitching the blades and incrementing the load. The clutches are disengaged and the brake is applied. This situation happens when the safe operating limits (emergency stop) have been exceeded or the wind speed rises above the cut-out wind speed (normal stop).

III. BATTERIES AND GENERATORS THEORY

The most frequent electrical components that someone meets at the electric circuit on the ship are batteries and generators. In this chapter, the theory of batteries and generators is presented along with the necessary remarks as pertain to the current study.

A. BATTERY THEORY

1. Battery Characteristics

A Battery is a combination of one or more electrochemical cells used to convert stored chemical energy into electrical energy. These cells are connected in parallel or in series to obtain the required current/voltage capability. To characterize the performance of a battery, specific terms are used.

First, the term equivalent series resistance (ESR) is defined as the internal resistance present in any cell that limits the amount of peak current it can deliver. The term amp-hour capacity is the most important factor for a battery specification. It is defined as the amount of current that a battery can deliver for one hour before the battery voltage reaches the end of life point. It represents the quantity of discharge current available for a specified length of time and at a certain discharge rate and temperature. In the case of a high discharge current, the battery capacity would be reduced and this would decrease its lifetime. Furthermore, the 'c' rate is currently equal to the amp-hour of the cell. The mid-point voltage (MPV) is the nominal voltage of the cell. It is measured when the battery has discharged 50% of its total energy. In the same way, the end of discharge voltage (EODV) is the voltage measured at the end of battery operational life. Gravimetric and volumetric energy density is a measure of how much energy a battery contains in comparison to its weight and its volume. Finally, ampere-hour efficiency of a storage battery is the ratio of ampere-hours output to the ampere-hours input required for recharge [12].

To specify which type of battery is better, its type, electrical performance, charge rate, maintenance needs, safety concerns, and reliability and economic expenses must be specified. A comparison test between different kinds of batteries should take into account all of these issues.

2.   Battery Storage

Battery use is vital in the hybrid system as it supplies the load demand whenever the energy from wind turbine is insufficient. When the supply from the wind turbine exceeds the load demand, the batteries are charged by turbine or diesel engine.

Some requirements should be also taken into account. First, the maximum energy allowed to be taken from or added to the batteries is usually 10% of total capacity. In addition, the minimum storage level is limited to 20% which is the value being available in the batteries before the discharge cycle begins [13].

When the energy from wind turbine exceeds the load demand, the batteries will be charged with-round trip efficiency according to the equation:

$$E_{bat(t)} = E_{bat(t-1)} + \frac{E_{wtg(t)} + E_{dg(t)} - E_{l(t)}}{n_{inv}} n_{bat} \qquad (3)$$

where:

$E_{bat\,(t)}$: The stored energy in batteries at hour t

$E_{b\,(t-1)}$: The stored energy in batteries at hour previous hour t-1

E_{wtg} : The energy generated by wind turbine at hour t

$E_{dg\,(t)}$: The energy from DG at hour t

$E_{l\,(t)}$: The energy of the load demand at hour t

n_{inv} : The efficiency of the inverter in percent

n_{bat} : The round trip efficiency of the batteries in percent.

When the energy of the load demand is greater than the available energy generated, the batteries will be discharged by the amount needed to cover the deficit. The energy stored in the battery at any time during the discharging mode is expressed as:

$$E_{bat(t)} = E_{bat(t-1)} - (\frac{E_{l(t)}}{n_{inv}} - E_{wtg})$$

(4)

To prevent batteries from being over charged or over discharged and to protect them against damage, the energy stored in the batteries at any hour (t) should be:

$$E_{batmin} \leq E_{bat(t)} \leq E_{batmax}$$

(5)

3. Battery Selection Criteria

The first issue in the selection of batteries is to identify which ones better support the hybrid system and can work in parallel mode with both the wind turbine and the diesel engine. According to the U.S. Energy System, the new stationary batteries that are designed to discharge and recharge daily are the best solution. This is because high cycle batteries reduce fuel consumption and overall operating costs.

For instance, a hybrid system using a quick-charge battery would alternate a 16-hour cycle of generator power with an 8-hour cycle of battery power. In the first cycle, the generator runs to supply the power load and recharges the battery simultaneously. In the next 8-hour cycle, the battery supplies the load while the generator is shut down. In hybrid quick-charge applications, cyclic control is necessary to achieve the previously described function.

The batteries should have sufficient capacity to provide the maximum peak power required by the load and to accept the maximum charge provided by the generator or the wind turbine. Otherwise, the battery may be damaged by the high current. The discharge capability of the battery should also be considered. It should be kept in mind that batteries that are discharged quickly will drop in voltage and may shut down the inverters and loads. A discharge factor of 5 or greater is usually recommended. This number is given relative to the rated capacity C of the battery.

4.   Battery Choice

Currently, the two main types of batteries being used in hybrid systems are nickel-cadmium and lead acid batteries. This study introduces a new type of battery: the valve-regulated lead acid (VRLA) battery. It is an advanced edition of the well-known lead acid battery with enhanced features and no maintenance needs [14].

First, the electrical performance of lead acid batteries has been increased with the VRLA design. There is considerable improvement of the rate and cold temperature performances. They are also virtually indistinguishable from their nickel-cadmium counterparts in turbine starting high rate performance. According to experimental results, the performance of the VRLA has also shown superior results.

Secondly, this battery has a very simple charge regime with ideal charge at high rate, constant voltage, or pulsed voltage. The high rate gives a fast recharge, which extends battery life.

Thirdly, and very important for ship application, is that no periodic maintenance is required. The battery simply needs to be put on a fixed replacement schedule. There are no other checks or maintenance required. At the end of the replacement interval, the battery should be removed and discarded.

Fourthly, the possibility for hazard explosion has also been minimized compared with the flooded lead-acid or nickel cadmium batteries. There is also reduced corrosion of surrounding structures and equipment due to acid mist or spray. The batteries would continue to function in an emergency situation even though they have severe mechanical damage. All these points increase the system and the ship safety and reliability.

Finally, and most importantly, the battery has a low 'Life Cycle Cost.' This is due to the low initial cost of the VRLA combined with the maintenance savings.

In conclusion, valve regulated lead-acid batteries provide electrical performance that compares well with nickel cadmium batteries. They can also provide excellent rate performance at low temperature. They are more reliable and safe for a ship application

and economically preferable. Unlike nickel cadmium batteries, there is no restriction for a limited upper operating temperature. Therefore, for the hybrid system the installation of the VRLA batteries is recommended.

5. Battery Use

At this point, a question to ask is: How can the required battery life and the needs of the hybrid system be achieved to provide the necessary power to the ship? This depends on the effect of the deep discharge in the cycle life of the battery, the time to recharge, the available charge current, and the end of discharge detection [15].

First, the battery cycle life depends on the amount of energy discharged at each cycle. In general, a battery has the capability to provide a finite amount of amp hours in its whole life. It is a general truth that if a certain amount is discharged at each cycle, the battery can provide many cycles. If the battery discharges totally at each cycle, however, the cycle life of the battery would be shorter.

Secondly, since many battery elements will be used to achieve the expected cycle life, they must be fully recharged and homogenous at each cycle. The available current should be sufficient for this purpose and recharged time can be reduced affectively with an alternate battery.

Thirdly, as mentioned, there is a need for sufficient current. If the price of the current is below the limit, the battery would not charge properly. For better performance, the use of the wind turbine or generator for recharging the battery should be at a minimum time.

Finally, overcharging affects the cycle life of a battery. Therefore, it is important to detect the end of discharge by measuring the amount of amp hours the system used. This has been achieved by battery manufacturers by estimating the cut-off voltage to a given depth of discharge.

Therefore, in the hybrid system, there should be an electronic controller that satisfies all these requirements and maximizes the life of the battery.

6. Battery Bank

In general, in hybrid systems, rather than requiring one battery, they require whole battery banks for storage of intermittent wind energy. In the case of low wind speed, a backup diesel generator is also necessary. The amp-hour capacity (CAh) and watt-hour capacity (CWh) of a battery bank required to supply a load for a certain period (day), when energy from the wind turbine or diesel generators is not available, is given by equation [16]:

$$C_{Wh} = \frac{E_L AD}{n_v n_{wh} DOD} \qquad (6)$$

where:

E_L = Load requirement (KW),

AD = Daily autonomy,

n_{inv} = Efficiency of the inverter,

n_{wh} = Efficiency of the battery bank,

DOD = Depth of discharge.

In the case study evaluation chapter, the total capacity of the battery bank will be estimated according to the number of the autonomy hours, which optimizes the earnings of the hybrid system.

B. GENERATORS THEORY

A generator is a device that converts mechanical energy into electrical energy. A generator forces electric charges to move through an external electrical circuit, but it does not create electricity or charge. This is already present in the wire of its windings.

The main classifications for generators are direct current, synchronous and asynchronous, subdivided into induction generators and permanent magnetic alternators. In operation, there are constant and variable rpm generators. A constant-rpm operation reaches maximum power coefficient at one wind speed. The variable-rpm operation up to

the rated wind speed is along the line of maximum power coefficient. The power output of variable-rpm wind turbines is smoother, with less flicker than the constant rpm wind turbine, and it can be used for voltage and frequency control in the grid.

There are many cases where a constant wind rotor rpm with induction or synchronous generator, or a variable wind rotor rpm with a double-fed induction generator, permanent magnet alternators, or direct-drive generators exist. The variable-frequency output is then converted to constant frequency.

A synchronous generator runs at constant speed, determined by the frequency and the number of poles, and draws its excitation from a power source external or independent of the load or transmission network it is supplying. They produce or generate alternating current (AC) when the unit's turbines are rotated by a motor. The yield frequency of the synchronous generator is precisely comparative to the speed at which the motor is powered. It has an exciter that enables it to produce its own reactive power and regulate its own voltage. A speed reduction gear is also required. Synchronous generators produce power by rotating electromagnetic fields surrounded by coils that generate a "three-phase alternating current." Synchronous generators are not commonly used because permanent magnets are apt to become "demagnetized" by the strong magnetic fields inside the synchronous generator. Another reason is that potent magnets that are made of rare metal are expensive.

An induction generator produces electrical power when its shaft rotates faster than the synchronous frequency of the equivalent induction motor. It has the ability to produce useful power at varying rotor speeds. This generator is mechanically and electrically simpler than other types of generators. The generator receives its excitation from the grid or electric utility. It has no means of producing or generating voltage until the generator is connected to the grid. It is direct drive; can only be run parallel with the grid; is tied to the frequency of the grid; and capacitor compensation is often used.

In reality, induction generators are used for wind turbines because induction motors are mass produced and inexpensive, the controls are simple, and they have reduced maintenance and operation costs. Synchronous generators would not be

acceptable for interface with the grid. This is due to complications of the control of the wind rotor rpm. A switching mechanism is responsible for the generator not operating below synchronous speed. The induction motor is brought up to synchronous speed and is then connected to the utility line. There is also a control mechanism, which turns the generator on and off, to measure rpm. At high wind speeds, it cuts out and restarts the generator after the winds have declined.

Generators are also divided into AC and DC types. AC generators required less maintenance and do not require as much additional circuitry to regulate their ever-fluctuating voltages. If DC power is desired to use in electronics, it is important to know that it is very unlean and requires a lot of filtering.

For variable-rpm operation, there is a choice between direct-drive generators and permanent magnet alternators. Both are direct-drive systems with no gearboxes. The direct-drive generator is very large, and the output is converted to constant frequency and voltage by power electronics. The permanent magnet alternator is very common on small wind turbines. The advantages are lower losses, lower weight, and lower cost [17].

IV. THE HYBRID SYSTEM

A. INTRODUCTION

Today, the main source for electrical power production for ships is diesel generators. In general, they are inexpensive to install; the specific fuel consumption is low; and they are a reliable solution. However, they are relatively expensive to operate and maintain. This is because major maintenance is needed every 2,000 to 20,000 hours, depending on the size of the diesel generator set.

Several studies have looked into ways to reduce the electrical supply needs of diesel generators and to minimize operational and maintenance costs. An attractive and potential solution is to install and use a wind turbine on a ship. The introduction of a wind turbine into the existing electrical power system on the ship may lead to a considerable reduction in the diesel fuel consumption as well as atmospheric pollution.

The installation of a wind turbine on a ship, however, is not such an easy issue. Its fluctuating power output makes the wind turbine unable to provide a ship's sole electrical requirements. Also, the need for survivability and operational readiness suggests adding the wind turbine to existing power plants, integrated wind diesels, or wind hybrid systems. Such an integration of wind with diesel systems may provide the reliability of the diesel system as well as the cost-effectiveness of the wind-generated energy.

B. CONCERNS

A hybrid system consists of many different parts and the integration of them may create many problems. First, there are concerns about voltage and frequency control, stop and starts of the diesel, use of surplus energy, and use and operation of the new technology.

Over all, the main concern is the dynamical stabilization of voltage and power for the consumer. The wind/diesel supply system should be designed to buffer the load fluctuations on the grid and the fluctuations of the wind turbine power output. This

requires an efficient control strategy, as well as fast-activating units. This system design should use the wind energy as much as possible, and the consumer should face a stable grid with the highest reliability as possible.

Secondly, to improve the cost-effectiveness of the hybrid system, the fuel consumption of the diesel generator must be minimized. Since diesel engines have low efficiency at low load, they should temporarily switch off when the average power of the wind machine, relative to the load, is high. The number of such switching actions, however, should be as low as possible to keep the mechanical wear at a low level and not increase the demand for maintenance.

Finally, the efficiency of this system must also be considered. Its performance depends not only on its general design, but also on the design and function of any single component part and the match between them. Low wind energy utilization arises from mismatch of wind availability and consumer requirements [18].

C.   COMPONENTS OF THE HYBRID SYSTEM

In general, a hybrid system may consist of many different components with different functions and designs. Following is an analysis of the main components of the hybrid system appropriate for the installation of a wind turbine on a ship.

1.   Storage Devices

An introduction of a storage device would solve many of the problems mentioned above. First, a system without storage and intermittent diesel operation leads to an unacceptably high diesel start numbers and increased fuel consumption. Secondly, the diesel operation runs for a prolonged time period below some specified minimum power level. Finally, if the diesel is turned off and the wind power is insufficient to cover the load, a system failure and a potential black out on the ship would happen.

At this point, the need for a storage system is obvious. This system should allow the diesel to be off as much as possible and insure that the diesel is operating at near peak efficiency. While the diesel is off, the system would be discharged until it reaches a minimum charge level. Then the diesel generator should be started. Its operation should

cover any wind power shortfalls and recharge the storage device. As the storage device is charged, the diesel power is reduced. The diesel should again shut off when the storage device has been fully recharged and the cycle repeats [13].

Research has also indicated that the incorporation of a short-term storage device into a wind-diesel system would further elevate the fuel savings potential; may further compensate for the fluctuations in the power output of the wind turbine; may further reduce operational hours of a diesel system; and reduce the excess energy generated. It has been shown that small amounts of storage can make a significant impact on the problem of high numbers of diesel stop/start cycles. As little as 12 min of storage can reduce the number of cycles to approximately one half that occurring without any storage [19].

Since there are different kinds of energy storage devices, an investigation must be done to determine which one most closely fits requirements. The storage medium should be convertible both to and from electricity. It should also be available at a reasonable price and should be capable of tolerating frequent and rapid changes in the direction and magnitude of energy flows without undue wear and maintenance. The system requirements demand high charge/discharge rates and specified storage duration [20].

With regards to the storage duration, it was found that the amount of diesel fuel used fell rapidly with increasing storage capacity for the first few hours of storage. Just a point beyond that, however, is where additional fuel savings did not justify the additional capital cost of the storage device. Therefore, this study concluded that storage capacity of few hours times the mean load is required. This storage capacity should not be small. This study predicted severe operational problems, such as the decrease in battery life due to the increase in the number of charge/discharge rates, would occur.

Batteries, flywheels, hydrogen, hydraulically, and thermal storage are the most common storage device systems. Batteries are the most common solution for storage requirements. With high rate batteries, however, such as nickel cadmium, the cost is increased and the cycle life is reduced. Flywheels have the advantage of compatible power transfer, but coupling them to the rest of the system is very difficult. Much more

work is needed on this topic. Also, if the moment of inertia is high, a flywheel becomes very hard to start. A hydrogen storage system is dangerous for a ship and the cost is very high. Hydraulic storage is very attractive because of low discharging rates, but this does not satisfied this study's requirements. Finally, thermal storage is the most attractive approach to longer-term energy storage. Therefore, it is evident that a battery storage system meets the requirements better and it would be the best solution for the hybrid system on the ship [20].

2.   Charge Controller

The vital role of a battery storage system for the hybrid system has been analyzed with the necessary objectives in mind namely to achieve the expected system requirements and to meet the needs of the hybrid system providing the necessary power to the ship. An electronic controller responsible to satisfy all these requirements is a charge controller.

A charge controller limits the rate at which electric current is added or drawn from electric batteries. It prevents overcharging and overvoltage which reduces battery performance and lifespan. To protect battery life, it also prevents deep discharging.

In general, a charge controller is the energy manager, ensuring that the battery is cycled under conditions that conserve its ability to deliver its rated capacity over its expected lifetime. It is responsible to switch off battery from the DC bus when it is fully charged and to disconnect the battery from the load when a certain level of discharge is attached. Therefore, it strongly influences the long-term reliability and maintenance costs of the hybrid system [21].

3.   Controllable Load (Dump Load)

A dump load should exist in the power circuit of a wind turbine. When a grid loss occurs, the dump load immediately applies an electrically absorbing load to the generator and, thereby, avoids excessive unloading of the generator and the wind turbine. The dump load resistor applies a load to the generator for at least a few seconds until the speed of the rotor is reduced, e.g., by blade pitching. To enable the operation of the

system with the diesel stopped, controllable load (dump load) is used to establish the grid frequency [22]. In this case, the generator should be disconnected from the diesel via the clutch. This produces the reactive power needed to keep the system voltage constant. The charge rate can also be limited by diverting current to a dummy load. A controllable load can also be used for over speed control of the wind turbine where the wind power exceeds the demand load during prolonged periods. For all these reasons, a dump load at the hybrid system is vital.

4. Diesel Generator

In many cases, the presence of a diesel generator for the hybrid system is vital. First, if the output power of the wind turbine is insufficient and this study's battery storage system cannot supply the load, the diesel generator should be able to cover the electrical needs of the ship. Also, in the case of peak loads or demand for permanent power supply, the diesel generator should cover the electrical demands. The diesel generator should also be able to charge the batteries.

At this point, the assumption that the existing generators at the ship cover these needs is true. These generators are well tested and cover high load demands when the ship travels. The reason to install the wind turbine at the ship, however, is to cover the load demands when it is away from the naval base, but when it is not travelling. These demands have a lower value and they are almost constant compared with the traveling load demands.

5. Rotating Phase Shifter

A rotating phase shifter is used to connect with the grid before the diesel power can be switched off. Then, the generator takes over voltage control and reactive power supply [23].

6. Inverter

An inverter is a device that changes DC power at its input into AC power at its output. It is also called a power converter. The resulting AC can be any required voltage and frequency with use of necessary transformers, switching, and control units. In the

hybrid system, the inverter should transform the DC voltage from the batteries to AC voltage necessary to the load. An inverter also performs the opposite function as a rectifier. The AC voltage is rectified to produce DC at any desired voltage. Thus, in the hybrid system, the output AC voltage from the wind turbine and the diesel engine can transform to DC voltage to charge the batteries. In a hybrid system, an inverter is also responsible for synchronization of phase and power transfer. It is also a safety device that functions to disconnect the wind turbine from the utility line when there is a fault in the utility line preventing overheating of the wires [21].

7. Electronics

Electronics use is the most important issue in the control of wind systems. There are controllers to monitor the condition of a wind turbine, power conversion, wind turbine control and operation which contains a number of computer processing units (CPUs) and programmable logic controllers (PLCs).

Power electronics are used to convert the variable-frequency and voltage power from the generator to the utility grid into constant frequency and voltage to ensure power quality .They are classified by AC to AC without a DC link and by AC to AC with a DC link [21].

In this study, since a hybrid system is used, the controller will be more complicated. It must have sensors and functions for faults to shut down the wind turbine if necessary; ability to measure wind speed and rpm to determine switches for starting up the motor; connection to the generator; and control for shutdown and over speed. Also, all the necessary information should be provided to an external computer. Also, the duty person in the ship's control room supervise continually the status and operating parameters, can change them, or can shut down the whole system in case of a fault alarm.

8. Wind Turbine

The use of the wind turbine and the kind of wind turbine being selected here were specified and discussed in the first two chapters.

D.   HYBRID SYSTEM ARCHITECTURE

1.   Architectures for Hybrid Systems

In general, the goal of the design of the hybrid system is to cover the load needs and to achieve the optimum economic earnings. This can be achieved by a correct selection and sizing of the system components and place them appropriately within the system structure. This structure can become complicated if the system has additional goals, such as charge batteries; reduce diesel fuel use; etc. The topologies in structure being used are series topology, parallel topology, and switched topology [24]. These topologies will be analyzed briefly below.

First, in the series topology, all the energy passes through the battery. Prior to this, the wind power energy and the diesel energy have been rectified to DC. An inverter then converts the DC energy from the battery to AC power to supply the load. Due to its simplicity, this system has controlled power loss and low costs for inverter and the diesel engine. The main disadvantages of the system are reduced overall efficiency; increased possibility of loss of power to the load with an inverter failure; and increased battery cost. A block diagram of this topology is shown in Figure 8.
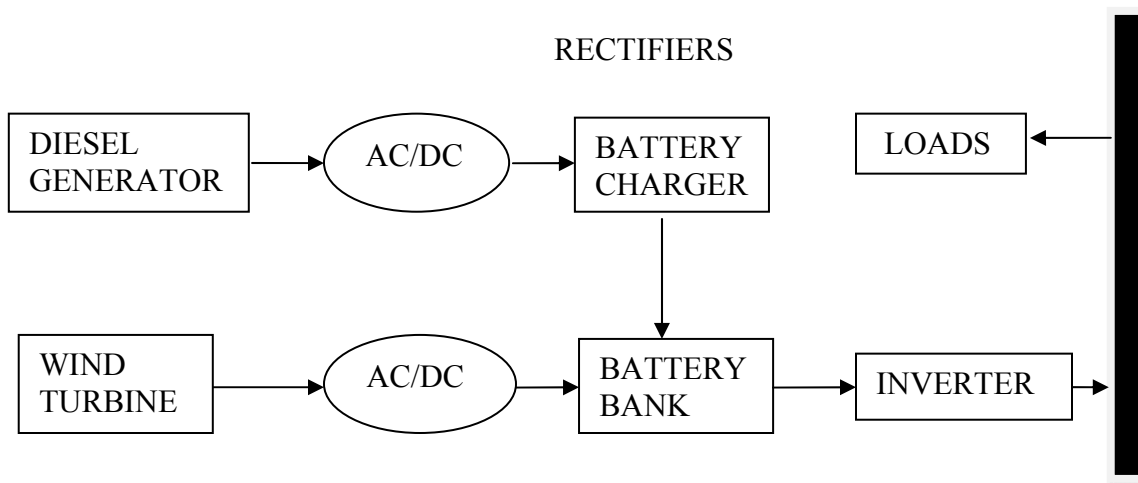
Figure 8.   The series topology of a hybrid system.

Secondly, is the switched topology, which is the most common installation today. In this topology, the diesel generator's supply directs the load or the inverter from the battery bank. The battery bank can be charged by the wind turbine or the diesel generator. Since the load can be powered from any source directly, the main advantage of this design is the redundancy. The drawbacks are increased cost of diesel engine and generator; power losses; and control difficulties. A block diagram of this topology is shown in Figure 9.
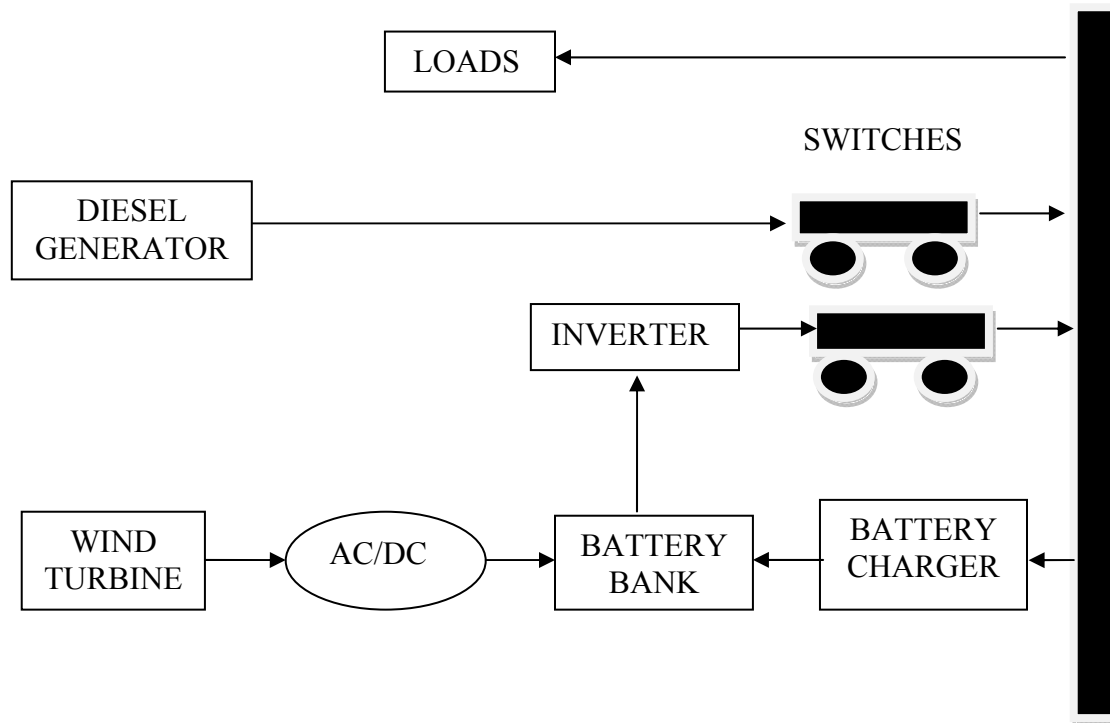
Figure 9.   The switched topology of a hybrid system.

Lastly, there is the parallel topology with more abilities. In this topology, load can be supplied by either source. Further, sources can be connected to the load at the same time. The inverter between generator and battery storage is bi-directional and can act as a battery charger or as a utility interactive inverter. The advantages of this topology are optimum system performance is possible; the cost is minimized due to the smaller inverter; and a battery storage bank and a diesel engine can be used. The main

disadvantage is that a complex integrated control system is required with increased cost. A block diagram of this parallel topology is shown in Figure 10.
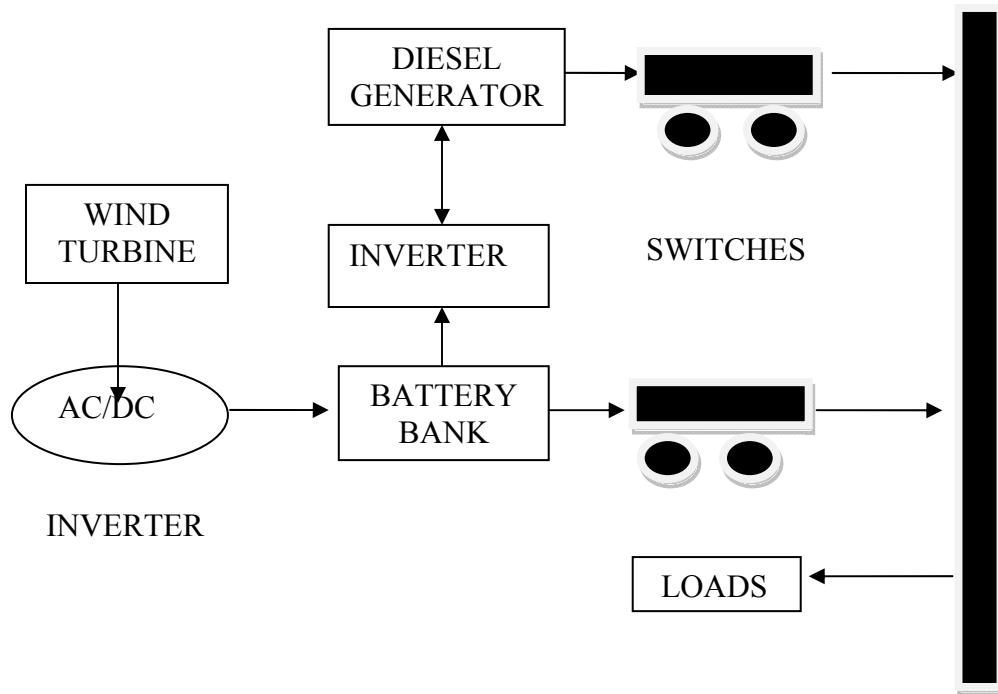
Figure 10.   The parallel topology of a hybrid system.

2.   Selected Topology for the Hybrid System

To select a topology for this study's system, the different functions that the system would meet must be presented. First, if the wind turbine provides sufficient energy, it would charge the batteries and supply the load. In the case that this energy provided by the load and the batteries is more than is necessary, a dump load would be connected to the electric circuit to consume the amount of the extra energy. Secondly, if the wind turbine generated power is not sufficient, the batteries would be used at the same time as the wind turbine. Thirdly, if the batteries are discharged beyond a point, the diesel engine with the wind turbine would supply the load and charge the batteries. Finally, in the case that the wind turbine does not operate, the diesel engine alone or with the batteries (if charged) would supply the load. A recommended block diagram of this topology is shown in Figure 11.
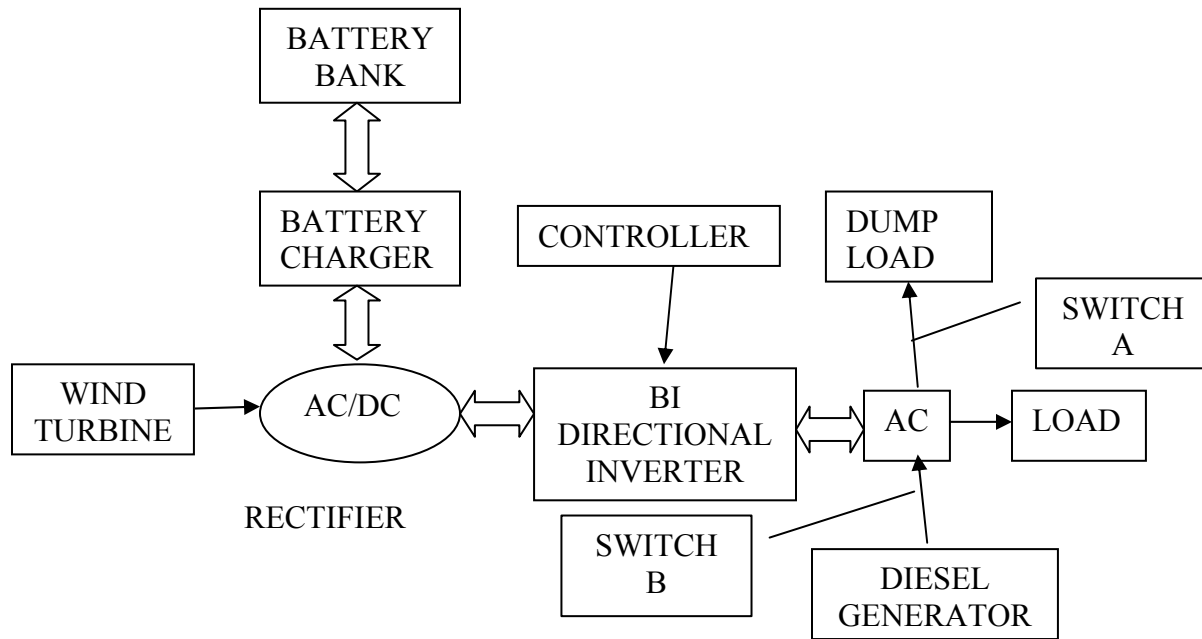
Figure 11.   The selected topology of a hybrid system.

According to Figure 11, and as described previously, success can be achieved with the different functions of the hybrid system. When the energy of the wind turbine is sufficient, switches A and B would be opened and the direction of the bi-directional arrow at the battery charger and the battery bank would be towards them. If the energy is more, switch A would be closed. When the wind turbine and battery storage are used, the direction of the bi-directional arrow would be away from them and the switches would be opened. When the wind turbine and diesel are used, switch B would be closed, switch A would be opened, and the direction of the bi-directional arrow at the battery charger and the battery bank would be towards them. Lastly, when the diesel engine is used alone, or with the batteries again, switch B would be closed, switch A would be opened, and the direction of the bi-directional arrow at the battery charger and the battery bank would be towards them or away of them, respectively [16].

This system is very different from the basic topologies analyzed previously. The reason is that this study's goals are different and more complicated. The purpose is to minimize diesel fuel use and diesel engine run time and to provide electrical backup power, keeping the batteries charged.

V.   ECONOMICS THEORY

The most important parameter for selecting the installation of a hybrid system, consisting of wind turbine/diesel/battery storage on a ship, is the economic aspect. To decide, the overall earnings should at least exceed its overall costs within a time period up to the lifetime of the system. For the purpose of this study, the lifetime of the hybrid system equals the lifetime of the ship (operational lifetime) and it is about twenty-five (25) years. The cost of the hybrid system includes acquisition costs, operating costs, maintenance costs, replacement costs. All these factors that affect economics will be analyzed below and some critical economic terms will be specified and calculated.

A.   INTEREST RATE

An important parameter for economic calculation is the interest rate. Interest rate is the price paid for the use of borrowed money or money earned by deposited funds. It is something like "rent of money." For instance, if money is deposited in a bank, interest is paid to the depositor as a percentage of the amount deposited. This percentage paid as a fee over a certain period of time is called the interest rate. The interest rate is used commonly over one month or one year.

Therefore, interest is considered the price of credit and it is subject to distortions due to inflation. Inflation is the rise in the general level of prices of goods and services in an economy over a period of time. When a price level rises, however, each unit of currency buys fewer goods and services. Thus, the purchasing power of the money faces a loss in real value. A measure of price inflation is the inflation rate (i). Inflation rate (i) is the annualized change of prices for goods or services over time. In reality, inflation means a decrease in the real value of money and other items over time. Each item may have its own inflation rate. For simplicity in this study, the same inflation rate for all calculations is used.

Interest rate is also divided into simple interest and compound interest. Simple interest is calculated only on a principle amount or on that portion of the principal amount which remains unpaid. Compound interest arises when interest is added to the

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principal, so that from that moment on, the interest that has been added also earns interest. Nominal interest rate is the price of a good before adjustment to inflation and it is visible to the consumer. Real interest rate is approximately the nominal interest rate minus the inflation rate. Also, nominal interest is composed of the real interest rate plus inflation. A simple formula for this is:

$$p_i = r_i + i \tag{7}$$

where:

p_i = nominal interest,

r_i = real interest,

i = inflation rate.

B. DISCOUNT RATE

The discount rate is an interest rate a central bank charges depository institutions that borrow reserves from it. A central bank is a banking institution that has the privilege to lend its currency. Depository institution is a financial institution allowed to accept monetary deposits from consumers. Therefore, the discount rate (d) refers to the fact that if there is a discount rate (d) how much interest can be earned.

C. PAYBACK TIME

The primary goal of the installation of a wind turbine is that at least the overall earnings equal the overall cost during the lifetime of the system. There are cases where earnings never exceed the costs, or were lower. The time at which earnings equal cost is called the payback time. The general idea is that it be as soon as possible.

The overall cost includes the initial costs and the costs of annual operation and maintenance. A supposition is made that the maintenance needs can be performed by the ship's crew of the ship in most cases. This can be achieved if the crew has the appropriate training. This study also estimates the annual energy production of the system and predicts the price of energy displaced.

The price of energy displaced would be the amount of money that is spent to produce 1 kWh of energy using the diesel engine of the ship. This prediction is driven primarily by the cost of oil. The price of the oil, however, could not be predicted precisely. It depends on many different parameters. Historical data shows that price increases have not been and will not be uniform. The most important factors are the estimated total reserves and the recoverable amount. For the purpose of the project, the estimated price given by the Department of Energy is used.

At the estimation of the payback time, general assumptions are that the same power outcome of the wind turbine is produced each year and the value of electricity is constant. Also, an average value of FCR for twenty five years will have been assumed for the price of energy displaced considering FCR to be the value of interest that would have been received from displaced money from savings.

The equation that predicts the payback time is the following [17]:

$$SP = \frac{IC}{((AKWh * \$/KWh) - IC * FCR - AOM)}$$ (8)

where:

FCR   = fixed charge rate per year,

IC   = initial cost of installation,

AKWh   = annual energy production, kWh/year,

$/kWh   = price of energy displaced,

AOM   = annual operation and maintenance cost, $/year.

D.   COST OF ENERGY

Today, all the ship's electrical needs have been provided by diesel generators. If in this study the electrical power provided by the diesel generator is replaced by that provided by a wind turbine, the cost of energy of the wind turbine must be compared with that of the diesel generator.

Cost of energy is the value of the energy produced by a system over the lifetime of the system. It depends on: the initial installed cost (IC); the fixed charge rate per year (FCR); the annual operation and maintenance cost (AOM); the fuel cost for convectional plants (FC); and the annual energy production (AKWh). There is also a levelized replacement cost term (LRC) which considers the cost for major overhauls and replacements over the lifetime of the system Therefore, the cost of energy (COE) equation is [17]:

$$COE = \frac{IC*FCR + LRC + AOM + FC}{AKWh}$$ (9)

E.   LIFE CYCLE COST

At this point, another concern is the amount of money that must be paid for a wind turbine on a ship over the lifetime of the system. This is the life cycle cost (LCC) and includes the total cost of the system, including all expenses incurred over the life of the system. Life cycle cost depends on: the initial installed cost (IC); energy cost which is the sum of all yearly fuel costs (E); sum of all yearly overall and maintenance costs M; sum of all yearly replacement costs R and salvage value; and net worth at the end of final year. Therefore, the life cycle cost (LCC) equation is [17]:

LCC=IC+M+E+R-S (10)

where everything has been estimated with present value.

F.   INTERNAL RATE OF RETURN

In general, the internal rate of return on an investment or potential investment is the annualized effective compounded return rate that can be earned on the invested capital. Therefore, with the hybrid power system it is the projected return on the investment of installing it. It represents the rate at which the initial capital expense could be invested to obtain the same return over the project life. In the calculation of the project rate of return, the yearly cash flows of the project are discounted back to the present using varying discount rates. The internal rate of return (r) is given by the following equation [25]:

$$C_S = \sum_{n=1}^{n} \frac{\mathrm{Pr}(n)}{(1+r)^n}$$

(11)

where:

C_S = System installed capital cost,

$\mathrm{Pr}(n)$ = Yearly profit of the system.

The discount rate is adjusted until the present value of the project, represented by the right side of the equation equals the installation cost of the project.

G.   TIME VALUE OF MONEY

To calculate the life cycle cost, it must be understood that there are operating and procurement costs of an item that are incurred at the time of acquisition. This would include costs such as initial installation, and other costs incurred at later times, such as operational costs.

The time value of money, however, is not constant. It is the value of money in a given amount of interest earned over a given amount of time. For example, 50 dollars today invested for one year with 5 percent interest rate will be worth 52.5 dollars after one year. Therefore, 50 dollars paid now or 52.5 dollars paid after one year with 5 percent interest rate has the same value.

This study calculates all costs at present value. Future costs are converted to present costs with the appropriate equations. Finally, hybrid system life cycle costs and existing diesel system costs are compared according to the present value of money.

H.   PRESENT VALUE

As mentioned, everything must be calculated at the present value with the correct equations. Present worth value is the value of an item today of a future payment, discounted to reflect the time value of money and other factors such as investment risk. Therefore, to estimate the present worth, all cash flows must be converted to a common point in time, the present.

The assumption is anticipating buying something at n years from now. The value of this product at n years from now is the future value (FV). The present value (PV) is obtained using a constant discount rate, d. The present value (PV) of the product is given by the equation [17]:

$$PV = \frac{FV}{(1+d)^n} \tag{12}$$

The net or lifetime present value (NPV) of a disbursement is a summation of the yearly present values [17].

$$NPV = \sum_{n=1}^{N} \frac{PV}{(1+d)^n} \tag{13}$$

Finally, the levelized annual cost (X_L) is the annuity one would pay out yearly given the constant discount rate, d [17].

$$X_L = NPV \frac{d(1+d)^N}{(1+d)^N - 1} \tag{14}$$

VI. COST ANALYSIS OF THE HYBRID SYSTEM

To estimate the cost of the hybrid system, the cost of all components included in the system must be taken into account. The system consists of a wind turbine, diesel generator, batteries, controllers, bi-directional inverter, power electronics, cables, etc. For all these components, acquisition costs, operating costs, maintenance costs, and replacement costs must be calculated. Among the costs related to diesel generators, wind turbine, batteries, and inverter will be analyzed. For the rest of the components, an extra cost has been used in the simulation program.

A. DIESEL GENERATORS

Since diesel generators already exist in the studied ship, they need not be replaced with new ones for the hybrid system. This research uses the existing generators and, therefore, their installation cost is ignored. Their maintenance cost, however, is taken into account. The use of the hybrid system would reduce the operating hours of the generators and maintenance needed. Since maintenance is a critical factor, determining functions and calculating their costs at present value must be done with or without the hybrid system.

Maintenance needs of a diesel engine depend on operating hours. The lifetime of the existing diesel at the studied ship is 30000 operation hours. In general, during this lifetime, at least the following maintenance needs must take place:

i) Oil and oil filter replacement every 250 hours,

ii) Air filter replacement every 500 hours of operation,

iii) Fuel filter replacement every 1,000 hours of operation,

iv) Replacement of governor oil every 4,000 hours of operation,

v) Overhaul service every 6,000 hours of operation.

B. WIND TURBINE

In general, wind turbines are manufactured in many shapes and sizes and their total costs vary. This depends on the cost of financing when the purchase agreement was executed, construction contracts, project size, type of the wind turbine, project location of installation, and many other factors.

Cost of components of a wind turbine include wind source assessment, site analysis expenses, freight of the turbine, major cost of the tower, necessary studies, construction expenses, system upgrades, protection, control equipment, transformers, operation, warranty, maintenance, repair, and insurance, etc.

It is true that it is difficult to estimate how much a wind turbine would cost. This varies according to negotiations with engineering and reducing overall costs in the production process. Furthermore, the initial costs per kilowatt power decreases as the rated power of a wind turbine increases. For instance, the price of a commercial wind turbine varies from $1.2 to $2.6 million per MW of nameplate capacity installed. The same turbines 2 MW in size cost roughly $3.5 million. Also, residential smaller scale wind turbines cost less overall, but they are more expensive per kilowatt of energy production. In general, a wind turbine under 100 kilowatts costs roughly between $3,000 and $5,000 per kilowatt of capacity.

Operation and maintenance (O&M) cost is a significant part of the total money spent for a wind turbine through its lifetime. Costs include insurance, regular maintenance, repair, spare parts, and administration. Insurance and regular maintenance can be covered by contract. The cost of repairs and related spare parts, however, is difficult to predict, and it increases as the wind turbine gets older.

As the wind turbine ages, some parts will wear out. Such parts as alternator, bearings and yaw bearings would need replacement. Also, environmental conditions of the operation, including dust and debris, will erode the blade materials, leading edge tapes, and paint coatings. Tail bushings and governor components, subjected to dirt and moisture; inevitably wear as the turbine governs in storms or during windy periods. Paint

coatings, subjected to sunlight, moisture, and temperature extremes, will eventually deteriorate. In addition, the lubricant in the gearbox will degrade over time.

Therefore, estimating of O&M costs is highly unpredictable, especially around the end of the life of the turbine. In general, for a new turbine, O&M costs are about 20-25 per cent of the total levelized cost per KWh produced over the life time of the turbine. When the turbine is new, the share is about 10-15 per cent, but this increases to 20-35 per cent as the turbine reaches the end of its life.

Another practical rule for estimating the O&M of a direct drive wind turbine, very simply, is to assume that the annual operation and maintenance expenses are about 1% of the installed cost. For instance, if the installed cost was $100,000, the O&M cost would be $1,000 per year. This amount of money should be banked on an annual basis over the life of the system. If the wind turbine has a gearbox, it should be assumed that the operation and maintenance cost is at least 2 % of the installed cost.

C.   BATTERIES

The role of a battery storage system is vital for a hybrid system. Since the valve-regulated lead acid batteries have been selected, there is no need for maintenance. Only the replacement cost would be taken into account. This cost depends on the lifetime of the battery. To prolong the need for replacement, the requirements for proper use must be satisfied.

One parameter frequently used in analyzing the economics of a hybrid system is the battery cycling cost C_{bw} ($/kWh). This cost can be estimated by the equation [15]:

$$C_{bw} = \frac{C_{batt}}{E_{batt} X_{typ} L_{typ}}$$

(15)

where:

C_{batt} = the cost of the battery bank ($)

E_{batt} = the energy capacity of the battery (kWh)

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X_{typ} = the typical depth-of-discharge

L_{typ} = the number of cycles expected at the typical depth-of-discharge.

Usually for the depth of discharge, the maximum depth of discharge is used to allow the battery to reach its cycle life at this depth of discharge. Otherwise, the typical depth of discharge is known only with simulation.

D.   FUEL CONSUMPTION

The purpose of installing a wind turbine on the ship is to minimize the fuel consumption of the diesel generators. This can be done by decreasing the time that the diesel generators are in operation covering load demands.

To estimate this decrease in fuel consumption, specific fuel consumption curves of the diesel generators must be used. A specific consumption curve relates the specific fuel consumption of the diesel loading (Figure 12). Specific fuel consumption (SFC) is a term used to describe the fuel efficiency of an engine design. It measures the amount of fuel needed to provide a given power for a given period. It is dependent of the diesel design. The differences in the specific fuel consumption between different engines tend to be small.

The fuel consumption curves are provided by the manufacturers of the diesel engine. In general, a diesel engine has high fuel consumption at idling conditions (no load) and maximum energy production at a rated capacity. Another characteristic of diesel engines is that their mechanical efficiency is reduced significantly for reduced engine power or speed or output. When the engine is operating at reduced power, this results in increased specific fuel consumption. Thus, at operating areas with low load, the efficiency decrease rates are high enough. According to these parameters, the hybrid system with the appropriate electronic controllers should satisfy that the diesel engine works within a certain region where the pay off outcome between power output and the fuel consumption is amenable. At areas with low load, the diesel engine should shut down.
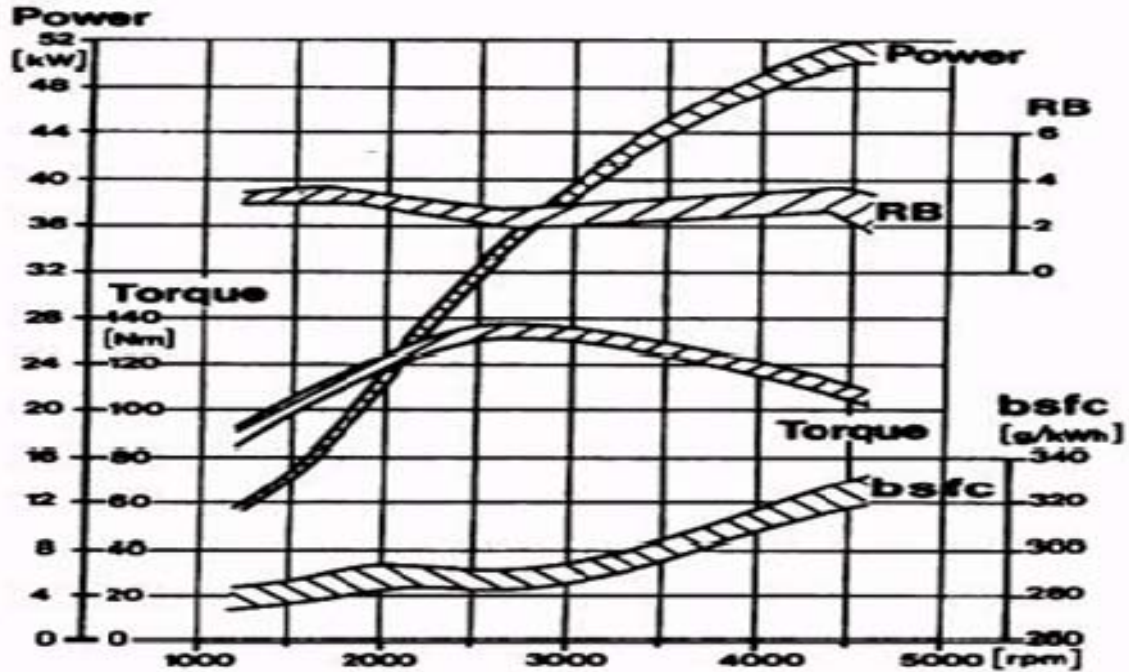
Fig. 35 — Scatter band of engine data (4-cylinder turbo Diesel engine)

Figure 12.   A typical figure of a specific fuel consumption curve. From [26]

Since using the curve to estimate fuel consumption for all operational loads according to the frequency they incur would be complicated and estimates would be time consuming, a more practical solution must be identified. A mathematical model should be used for the fuel cost to determine the economic operation of the hybrid system.

In general, manufactures have measured the power output of the diesel engine at the rated speed. This is called the rated power output and is referred as rated PTO. In most cases, the rated power is not the maximum power. Therefore, for the diesel engine, the rated power and fuel consumption is known at the rated engine speed. According to Skarstein and Uhlen's equation, the fuel consumption q [liter/h] can be expressed as a function of the diesel-rated power PTO [KW] and the operating power P_d [KW] according to the equation [27]:

$$Q = 0.246P_d + 0.08415PTO \qquad (16)$$

According to experimental data, when the net load (ship electrical load-wind turbine power) is greater than the critical load, it is more economic to meet the load by running the diesel and using the diesel directly. When the load is less than a critical load, however, it is more economic to use the energy that was previously stored in the battery by the diesel operation in excess of the load at that time. This critical load can be calculated by the equation [27]:

$$L_c = \frac{C_f F_o}{C_{be}} \qquad (17)$$

where:

C_f = Cost of fuel ($/liter),

F_o = Diesel no-load fuel consumption (liters/hr),

C_{be} = Cost of battery erosion ($/kWh).

Finally, in the hybrid program used for the output calculations for this project, a linear fuel curve is utilized in place of a more complicated curve. This represents the fuel use and results in some small mistakes. This curve connects the points between the fuel consumption of the minimum power level and the rated diesel power level [25].

E.   INVERTER

To find the cost of the inverter, how much power is actually produced and fed into the electric grid must be specified. At this point, it is important to introduce a new term: efficiency of an inverter. An inverter, like any electrical device, has heat losses. Thus, the real energy is reduced. A typical inverter has an efficiency of about 94%; therefore, about 6% is lost in the conversion process. Inverter efficiency is defined as:

$$n_{inv} = \frac{P_o}{P_o + P_l} \qquad (18)$$

where:

Po = Output power (KW),

P_l = Total power loss (KW)

Efficiency ratings, however, are usually given in a resistive mode. In contrast, in the hybrid system, efficiency consists of the efficiency of both the inverter and the waveform. Waveform efficiency means that the electronic appliances run better and use less power with a pure sine wave. Any other waveform that is not a true sine wave will be less efficient when powering inductive loads and more power would be needed. Thus, to choose the inverter, searching for the desirable efficiency for the particular hybrid system is important. Therefore, the cost of an inverter depends on rated power, voltage range at input and output, and efficiency.

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VII. CASE STUDY EVALUATION

The purpose of this project is to provide the energy supply of the ship's required constant load at different occasions by the hybrid system, and minimizing the fuel consumption of the diesel engines at the same time. To achieve this, the components of the hybrid system should be sized properly. Since the diesel engines already existed at the ship, they are considered as a constant. The different sizing component options would be evaluated using economic terms, such as cost of energy, payback period, and internal rate of return.

A.   HYBRID2 SOFTWARE

The evaluation of the different sizing components options of the system requires a long-term prediction of the hybrid power system performance. For this purpose, the computer software Hybrid2 is used [28]. It is programmed in Microsoft Visual Basic and uses a Microsoft Access Database. It contains four parts: Graphical user interface (GUI); Simulation Module; Economics Module; and Graphical Results Interface (GRI). The GUI incorporates a library of projects, power systems, time series data, mechanical components, and a glossary of frequently used terms and definitions of all the program input parameters. The Simulation and Economics Modules allow the user to run simulations and includes error checking of inputs. The Simulation Module has the ability to run simulations with great variety of system architecture using various loads, wind turbines, photovoltaic (PV) arrays, diesels, batteries, converters, dump load on an AC and/or DC bus, and an extensive choice of dispatch algorithms. The independent Economics Module allows the performance of an economic analysis using system performance information from the simulation. Finally, the GRI allows the user to easily view the detailed output data in a graphic form.

B. COUPLED OCEAN/ATMOSPHERE MESOSCALE PREDICTION SYSTEM (COAMPS)

An important parameter for the Simulation Module of the Hybrid2 software is the meteorological data being given as an input. For this purpose, a coupled ocean/atmosphere mesoscale prediction software (COAMPS) developed by the Naval Research Laboratory is used in order to obtain realistic wind profiles [29].

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMS) is the latest product in a series of mesoscale model developments at the Naval Research Laboratory (NRL) Marine Meteorology Division (MMD). It represents state-of-the-art analysis and short-term forecast tools applicable for any given region of the Earth in both the atmosphere and ocean.

The atmospheric component of COAMPS can be used for real-data or for idealized applications. For the real-data applications, the COAMPS analysis can use either global fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) or the most recent COAMPS forecast as the first-guess. Observations from aircraft, ships, and satellites are blended with the first-guess field to generate the current analysis. For idealized experiments, the initial fields are specified using an analytic function or empirical data to study the atmosphere in a more controlled and simplified setting. The atmosphere model uses nested grids to achieve high resolution for a given area; it contains parameterizations for subgrid scale mixing, cumulus parameterization, radiation, and explicit moist physics.

The atmospheric system consists of the analysis and forecast components. The analysis executable is run first to prepare the initial and boundary files used in the forecast model. Then, the forecast executable performs time integration of the model numerics and physics. It then outputs prognostic and diagnostic fields in pressure, sigma, or height coordinates.

C.   INPUTS FOR THE CASE STUDY

The load of the hybrid system is considered to be constant. This AC load is 25 KW when the ship does not travel and it is away from its naval base; 60 KW when the ship travels; and it is assumed zero when the ship is at its naval base since the 25 KW of load demand will be covered by outer current supply. The total yearly load demand of the ship varies according to the ship's operational needs during the year. Therefore, it depends on the time that the ship travels and it is away from its naval base. It is also assumed that the load does not have any variability and that a daily load matrix has been used as an input for the hybrid 2 simulation program when the appropriate price for the load was given on a half an hour basis for all days of the year.

Another important assumption from this project is that the ship stays at three different specific harbors when it does not travel and it is away from the naval base. The historic yearly wind speed data of these areas has been used as an input at the simulation program. Again, a wind speed matrix has been used when wind speed values was given on a half an hour base for all days of the year. These values were given assuming that the ship stays specific days of the year at each harbor. Finally, the ship will use the wind turbine only at the harbors.

The components of the hybrid system, except from the diesel generators, have also been sized according to the area and operational and survivability constraints of the ship. Finally, the economic parameters of the system can vary independently, or with the other variables of the system, and can influence the economic savings of the system.

D.   BASE CASE STUDY

At this point, a base case scenario should be defined. This base case exists when the hybrid system consists of a wind turbine of 10 KW only and the necessary electrical circuits (transformers etc) to transform the outer 110V voltage and 60 Hz frequency of the wind turbine to 415V voltage 50 Hz frequency of the ship AC bus. This allows the ability to connect it. Space restrictions of the ship and the need for operational readiness make this ideal as the basic scenario. This is because a bigger power wind turbine would

take more space on the ship deck. Also, it would take time to remove the blades and put them on the deck. Due to the smaller blade ratio, this is not required for the base case wind turbine.

Also, the operational scenario chosen as the base case is ordinary for this type of ship. The ship stays about half the year at the naval base. This is to perform maintenance on its electrical and mechanical systems and to train the crew. It travels about two months in a specific area and stays about four months at the chosen three harbors. At these harbors only, the wind turbine would be used. The load also has been transformed for the needs of this operational scenario.

According to the operational scenario mentioned above, the ship will use the power of the wind turbine only for one third of the year. The wind turbine outer power (10 KW) also is less than the load demand at the harbors (25 KW). Therefore, there will not be excess energy from the wind turbine that cannot meet the load. Thus, there is no need for storage batteries and extra electrical devices that convert the DC output of the battery bank to the AC bus load demand. It is important not to forget that batteries and electronic devices are the major recurring expenses of a hybrid system. This is due to the high price and short operational life (about 10 years). For all these reasons, they are excluded from the components of the hybrid system for the base case scenario.

Finally, the economic inputs for the base case scenario should be defined. The economic data have been used as inputs in the hybrid 2 simulations is being demonstrated in Table 4.

Diesel fuel cost ($/l)	1.82
System financial life (yr)	25
Balance of system cost ($)	2,000
Installation overhead cost (%)	10
Hybrid system operation and maintenance cost ($/yr)	1,950
Diesel system only operation and maintenance cost ($/yr)	1,600
Salvage value of equipment (%)	5
Inflation rate (%/yr)	3
Discount rate (%/yr)	8.5
Fuel inflation rate (%/yr)	5
Down payment fraction (%)	100
Primary load ($/KWh)	0.1
Wind turbine capital cost ($)	32,940
Total installation cost ($)	2,000
Wind turbine overhaul cost ($)	1,000

Table 4. **Economic data for the base case.**

At this point, some terms that have been used above should be explained. The balance of system costs is the purchase and installation cost for any system equipment for the hybrid system not included elsewhere (transformers, switch gear, etc). The down payment fraction is the fraction of the total project cost (installed system cost) which is paid directly at the beginning of the project. It is assumed that the total project cost is paid directly so that there are no financing and loan payments. Salvage value is the amount of money obtained for the project equipment when sold at the project termination and it is given as percent of the original cost. The system financial life is the economic life of the system where all the economic calculations are performed. Lastly, the system

installation overhead cost is the general cost associated with the installation of the power system. It is given as a percentage of the total installation cost and it covers all the external expenses of installing a new power system [25].

Running the simulation program with the inputs mentioned above, results in the following outputs shown in Table 5.

Yearly load demand (KWh)	160,800
Yearly energy generated by wind turbine (KWh)	5,654.3
Yearly energy generated by diesel (KWh)	155,157
Yearly dump energy (KWh)	11.6
Yearly fuel consumed by hybrid system (l)	55,563.6
Yearly fuel saved by hybrid system (l)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/KW)	3,714
Useful System life (years)	25
Fuel cost ($/l)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per liter consumed ($/l)	2.984
Payback Period (years)	17.53
Cost of energy for hybrid system ($/KWh)	1.0637
Cost of energy for diesel only system ($/KWh)	1.068
Internal rate of return (%)	5.875

Table 5. **Base case results.**

According, to these results it is clear that the economic savings in the base case scenario, due to the wind turbine use, are not enough. The payback period for the system is about seventeen and a half years on a twenty five year system life; the internal rate of return 5.875%; and the cost of energy savings is very small (about 0.0043$/kWh) compared with the diesel-only system case. The reasons for this are the limited use of the wind turbine (only one third of the year) and the small power output capacity.

E.   SENSITIVITY ANALYSIS

At this point, the following cases are analyzed and the results are compared with the base case scenario mentioned previously. The reason is to see how each input parameter's initial price varies the final economic savings of the system and optimizes them.

1.   Wind Turbines of Different Power Output

First, this section examines how the power output of a wind turbine determines the economic savings. By selecting a bigger power output wind turbine, the number of hours that the diesel engine runs decreases and fuel savings increase. The initial cost of installation and maintenance is higher, however, and the impact of its size at the ship is severe. This refers to operational readiness, survivability, and naval architecture characteristics. In this next section, a 20 KW and a 40 KW wind turbine is examined.

2.   The 20 KW Wind Turbine

The selection of a 20 KW wind turbine determines the non-use of storage batteries and electrical devices converting voltage for the same reasons mentioned in the base case. The 20 KW wind turbine technical data selected is represented in Table 6 and with a selected image in Figure 13.

Rated power	20 kW
Rated wind speed	14 m/sec
Start-up wind speed	2 m/sec
Cut-in wind speed	3 m/sec
Furling wind speed	16 m/sec
Rotor diameter	10.4 m
Magnetic material	Ne-Fe-B
Blade material	Pultruded fibreglass
Weight	750 Kg
Over speed protection	Rotor pitch, Auto tail furl
Generator (direct drive)	36 pole tail furl
DC charge voltages	240V
DC charge controller	PWM shunt regulator

Table 6. **The technical specifications of 20 KW wind turbine. From [9]**

Figure 13. **The 20 KW wind turbine. From [9]**

The economic inputs for the 20 KW wind turbine scenario are shown in Table 7.

Diesel fuel cost ($/l)	1.82
System financial life (yr)	25
Balance of system cost ($)	3,000
Installation overhead cost (%)	10
Hybrid system operation and maintenance cost ($/yr)	2,200
Diesel system only operation and maintenance cost ($/yr)	1,600
Salvage value of equipment (%)	5
General inflation rate (%/yr)	3
Discount rate (%/yr)	8.5
Fuel inflation rate (%/yr)	5
Down payment fraction (%)	100
Price of regular power ($/KWh)	0.1
Wind turbine capital cost with tower ($)	59,190
Total installation cost ($)	4,000
Wind turbine overhaul cost ($)	2,000

Table 7. **Economic data for the 20 KW wind turbine.**

Running the simulation program with the inputs mentioned above, results in the following outputs shown in Table 8.

Yearly load demand (KWh)	160,800
Yearly energy generated by wind turbine (KWh)	11,722.2
Yearly energy generated by diesel (KWh)	149,813
Yearly dump energy (KWh)	732.3
Yearly fuel consumed by hybrid system (l)	54,455.8
Yearly fuel saved by hybrid system (l)	2,281
Diesel #1 operating (h)	4,416
Diesel #2 operating (h)	1,440
Diesel #3 operating (h)	1,440
Diesel #4 operating (h)	0
Total system installed cost ($/KW)	3,329.5
Useful System life (years)	25
Fuel cost ($/l)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per liter consumed ($/l)	2.984
Payback Period (years)	16.08
Cost of energy for hybrid system ($/KWh)	1.056
Cost of energy for diesel only system ($/KWh)	1.068
Internal rate of return (%)	6.637

Table 8.   20 KW wind turbine results

Comparing these results with the base case scenario, it is obvious that the economic savings of the system are better. The payback period of the system is reduced to about sixteen years; the internal rate of return is increased to 6.637%; and, compared with the diesel-only case, the cost of energy savings is bigger (0.012 $/KWh) than that of the base case scenario (0.0043$/kWh). Again, since the time that the ship uses the wind turbine is small (only one quarter of the year) and the price of installation and maintenance of the system is double compared to the base case scenario, there is no significant difference of economic savings.

3.   The 40 KW Wind Turbine

The installation of the 40 KW output power wind turbine enhances the idea of the installation of a whole hybrid system on the ship. Because this output power exceeds the ship's load at the harbors (25 KW), there will be excess energy at the system up to 15 KW. This energy should be used to charge the batteries so that the batteries can meet the load when they discharge and minimize the operational hours of the diesel generators. This would lead to reduced fuel consumption. The design configurations of such a system; the technical data of the components; and an optimization of the savings resulting from changing the number of batteries is listed below.

a.   *Design Assumptions of the Hybrid System*

To design the hybrid system correctly, it is necessary to examine the technical data of the components. The wind turbine has a rated power of 40 KW, an AC voltage of 480V, and 60 Hz frequency. The diesel generators have rated power 40 KW, 415 V AC with frequency 50 HZ. The load is AC with power 60 KW or 25 KW. This depends on if the ship travels or not and that the batteries have DC voltage output. The AC bus of the ship is 415V 50 Hz and the DC bus of the ship is 120V. Therefore, the battery bank should be connected to the DC bus and the wind turbine, diesel generators, and the load at the AC bus. Before the wind turbine can be connected to the AC bus, however, electronic devices (transformers etc.) should convert the output voltage and frequency to the appropriate values of the bus.

At this point, a bi-directional inverter should be matched with the output voltage of the AC and DC buses. The output voltage of the AC buses is 415V, 3-phase with frequency of 50 HZ. According to the inverter manufacture technical data, a bi-directional inverter of rated power 15 KW is recommended. The DC nominal voltage for this inverter is 120V.

This DC nominal voltage should be the output voltage of the battery bank. Since the nominal voltage for each battery is 12V, 10 batteries should be connected in series to obtain the required DC voltage output (10*12=120V). The number of batteries being connected in parallel mode determines the period of the autonomy of the system when the load is being supplied only by the batteries. This parameter is a variable and has to be calculated to achieve the maximum economic savings.

Finally, to obtain the maximum economic savings from the hybrid system, the diesel engines should work as little as possible. They would shut down when the wind turbine and batteries can meet the load. In case this is not possible, they would start up to meet the load. The batteries should also not be discharged below a point (to obtain the desired operational life). If this point is about to be reached, the diesel engine should start to charge them, too. It is also recommended that the charge of the batteries by the diesels not exceed a certain point for the prevention of battery wear. Lastly, the diesel engines minimum time, per the manufacturer, equals one hour and this parameter has also been taken into account for the hybrid 2 program calculations.

b.   *Optimization Analysis of the Hybrid System*

To determine the optimum economic savings solution, the components of the hybrid system would be sized. According to the design assumptions mentioned above, only the number of batteries in parallel mode can be sized (for different autonomy hours of the hybrid system).

In general, the largest recurring cost in a wind-hybrid system with battery storage is battery replacement. The cost of this replacement depends on the type and the technical data of the battery. The type of the battery of this hybrid system is sealed valve regulated acid battery. Therefore, nominal voltage and capacity of the battery are the

variables used to estimate the optimum economic profit solution. As a first step, the capital cost of two different capacities' batteries with the same voltage (6V) would be compared according to Table 9.

Autonomy Hours	Required Capacity	Number of Batteries 6 V/1.3 AH	Capital Cost($) (7.4$/unit)	Number of Batteries 6 V/12 AH	Capital Cost($) (20.9$/unit)
1	39.111	602	4,454.8	66	1,379.4
2	78.222	1,204	8,909.6	131	2,737.9
3	117.333	1,820	13,468	200	4,180
4	156.444	2,420	17,908	260	5,434
5	195.555	3,020	22,348	340	7,106
6	234.666	3,620	26,788	400	8,360
7	273.777	4,220	31,228	460	9,614
8	312.888	4,820	35,668	540	11,286
9	351.999	5,420	40,108	600	12,540
10	391.11	6,020	44,548	660	13,794
11	430.221	6,620	48,988	720	15,048
12	469.332	7,240	53,576	800	16,720
13	508.443	7,840	58,016	860	17,974
14	547.554	8,440	62,456	920	19,228
15	586.665	9,040	66,896	980	20,482
16	625.776	9,640	71,336	1060	22,154
17	664.887	10,240	75,776	1120	23,408

Autonomy Hours	Required Capacity	Number of Batteries 6 V/1.3 AH	Capital Cost($) (7.4$/unit)	Number of Batteries 6 V/12 AH	Capital Cost($) (20.9$/unit)
18	703.998	10,840	80,216	1,180	24,662
19	743.109	11,440	84,656	1,240	25,916
20	782.22	12,040	89,096	1,320	27,588
21	821.331	12,640	93,536	1,380	28,842
22	860.442	13,240	97,976	1,440	30,096
23	899.553	13,840	102,416	1,500	31,350
24	938.664	14,460	107,004	1,580	33,022

Table 9.   **Cost calculations at two different capacities.**

According to the results of the above table, it is obvious that for the same output voltage of battery 6V, cost decreases with the increase of the capacity of the battery. Therefore, for the hybrid system, this study's research suggests choosing batteries with the maximum capacity at a given voltage. At this point, a comparison test of the capital costs would be performed for the different voltages 6V and 12V batteries at the maximum battery capacities being available at the market. This would be done to identify the most profitable solution. The batteries with a nominal voltage of 2V would not be concluded at this test since we would need a large number of batteries in series (200 batteries). This would result in a highly increased capital cost. Batteries of nominal voltage more than 12V have increased cost also and are not commonly being used. They would also be excluded in this study.

Autonomy Hours	Required Capacity	Number of Batteries 6 V/12 AH	Capital Cost (20.9$/unit)	Number of Batteries 12V/70 AH	Capital Cost (121.8$/unit)
1	39.111	66	1,379.4	10	1,218
2	78.222	131	2,737.9	20	2,436
3	117.333	200	4,180	20	2,436
4	156.444	260	5,434	30	3,654
5	195.555	340	7,106	30	3,654
6	234.666	400	8,360	40	4,872
7	273.777	460	9,614	40	4,872
8	312.888	540	11,286	50	6,090
9	351.999	600	12,540	60	7,308
10	391.11	660	13,794	60	7,308
11	430.221	720	15,048	70	8,526
12	469.332	800	16,720	70	8,526
13	508.443	860	17,974	80	9,744
14	547.554	920	19,228	80	9,744
15	586.665	980	20,482	90	10,962
16	625.776	1,060	22,154	90	10,962
17	664.887	1,120	23,408	100	12,180
18	703.998	1,180	24,662	110	13,398
19	743.109	1,240	25,916	110	13,398
20	782.22	1,320	27,588	120	14,616

Autonomy Hours	Required Capacity	Number of Batteries 6 V/12 AH	Capital Cost (20.9$/unit)	Number of Batteries 12V/70 AH	Capital Cost (121.8$/unit)
21	821.331	1,380	28,842	120	14,616
22	860.442	1,440	30,096	130	15,834
23	899.553	1,500	31,350	130	15,834
24	938.664	1,580	33,022	140	17,052

Table 10.   Cost calculations at two different nominal voltage and capacity.

From the results of Table 10, it is concluded that using the sealed lead valve regulated batteries with nominal voltage of 12V and capacity 70 AH is the most profitable solution. At this point, the autonomy hours of the battery bank should be figured out, according to the economic outputs of the hybrid 2. Economic terms, such as the payback period and the internal rate of return, would be compared at the different autonomy battery hour cases. These results are shown in Table 11.

Autonomy Hours	Capital Cost of Batteries	Payback Period (years)	Internal Rate of Return (%)
1	1,218	12.83	7.682
2	2,436	11.61	8.744
3	2,436	11.62	8.731
4	3,654	10.99	9.325
5	3,654	10.98	9.333
6	4,872	10.65	9.634

Autonomy Hours	Capital Cost of Batteries	Payback Period (years)	Internal Rate of Return (%)
7	4,872	10.62	9.664
8	6,090	10.55	9.688
9	7,308	10.54	9.647
10	7,308	10.53	9.657
11	8,526	10.54	9.587
12	8,526	10.52	9.61
13	9,744	10.46	9.627
14	9,744	10.48	9.602
15	10,962	7.53	13.842
16	10,962	7.54	13.819
17	12,180	7.55	13.758
18	13,398	7.58	13.661
19	13,398	7.57	13.673
20	14,616	7.61	13.563
21	14,616	7.58	13.624
22	15,834	7.63	13.483
23	15,834	7.61	13.534
24	17,052	7.62	13.469

Table 11. **Economic parameters at different autonomy hours of the batteries.**

According to the results of Table 11, the shortest payback period is 7.53 years and the greatest internal rate of return is 13.842 % for the hybrid system. These results occur for 15 hours of autonomy ability of the battery bank. Therefore, it is concluded that the hybrid system should have 90 batteries total, 10 in series and 9 in parallel mode, to achieve the optimum economic savings.

c.   Technical Specifications of the Components of the Hybrid System and Final Results

According to the design configuration analyzed above, the components of the hybrid system are wind turbine of 40 KW, bi-directional inverter of 15 KW, battery bank of 12V batteries, and diesel generators of 40 KW each. The technical specifications of these components with some economic values used at the simulation program and a picture of the 40 KW wind turbine are illustrated in Tables 12, 13, 14, 15, 16 and Figure 14.

Manufacturer	Enertech
Model number	Series E44, 44/40
Rated Power	40 KW
Rated wind speed	30 mph
Start-up wind speed	12 mph
Cut-in wind speed	8 mph
Cut-out wind speed	60 mph
Rotor diameter	13 m
Rotor type	Fixed Pitch
Yaw control	None-rotates full 360 degrees
Wind plant Weight	4,100 lb
Generator type	3-phase induction, 480 V AC, 60 Hz
Generator speed	1800 rpm cut-in, 1850 rpm max
Brake	Electro-mechanical disc, self adjusting
System design life	25 years

Blade material	Fiberglass composites
Capital cost ($)	110,000
Tower capital cost ($)	7,000
Installation cost ($)	8,000
Overhaul costs ($)	4,000
Overhaul period (yr)	10

Table 12. **The technical specifications of the 40 KW wind turbine. From [30]**

Figure 14. **The 40 KW wind turbine. From [30]**

Rated power (KW)	15
Bi-directional inverter capital cost ($)	19,500
Bi-directional inverter installation cost ($)	300
Bi-directional inverter efficiency (%)	94
Inversion no load loss (KW)	0.45
Life (yr)	10

Table 13. **The technical specification of the bi-directional inverter. From [31]**

Diesel generator rated power (KW)	40
Minimum allowed power (KW)	10
Capital Cost ($)	12,000
Overhaul cost ($)	400
Balance of plant cost	4,000
Diesel engine operation and maintenance cost ($/h)	0.025

Table 14. **The technical specifications of the diesel generator. From [32]**

Nominal voltage (V)	12
Nominal Capacity (Ah)	70
Charge rate limit (A/Ah remaining)	1
Capital cost ($) (per battery)	121.8
Operation/Maintenance cost (% /year)	5
Internal resistance (ohm)	0.0056
Battery efficiency (%)	85
Battery Life (yr)	9
Battery Bank scale factor	1
Initial Cap of Battery Bank (%)	100

Table 15. **The technical specifications of the battery bank. From [33]**

Diesel fuel cost ($/l)	1.82
System financial life (yr)	25
Balance of system cost ($)	4,000
Installation overhead cost (%)	10
Hybrid system operation and maintenance cost ($/yr)	3,000
Diesel system only operation and maintenance cost ($/yr)	1,600
Salvage value of equipment (%)	5
General inflation rate (%/yr)	3
Discount rate (%/yr)	8.5
Fuel inflation rate (%/yr)	5
Down payment fraction (%)	100
Price of regular power ($/KWh)	0.1

Table 16.   Economic data for the whole hybrid system.

Running the simulation program with the inputs mentioned above we have the following outputs shown in the Table 17.

Yearly load demand (KWh)	160,800
Yearly energy generated by wind turbine (KWh)	25,773
Yearly energy generated by diesel (KWh)	139,073
Yearly energy from storage (KWh)	6,990.4
Yearly energy into storage (KWh)	6,984
Yearly excess energy (KWh)	1,505.9
Yearly fuel consumed by hybrid system (l)	45,377.6
Yearly fuel saved by hybrid system (l)	11,359.3
Diesel #1 operating hours in hybrid system (h)	3,622.5

Diesel #2 operating hours in hybrid system (h)	1,444.5
Diesel #3 operating hours in hybrid system (h)	93.5
Diesel #4 operating hours in hybrid system (h)	0
Diesel #1 operating hours in base case (h)	4,416
Diesel #2 operating hours in base case (h)	1,440
Diesel #3 operating hours in base case (h)	1,440
Diesel #4 operating hours in base case (h)	0
Total system installed cost ($/KW)	4,044.95
Useful System life (years)	25
Fuel cost ($/l)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per liter consumed ($/l)	2.984
Payback Period (years)	7.53
Cost of energy for hybrid system ($/KWh)	0.945
Cost of energy for diesel-only system ($/KWh)	1.068
Internal rate of return (%)	13.842

Table 17.   The 40 KW wind turbine results.

Comparing these results with the previous cases, it is obvious that the economic savings of the hybrid system is the biggest. The payback period of the system is reduced to about seven and a half years; the internal rate of return is increased to 13.842%; and the cost of energy savings compared with the diesel-only case is bigger (0.123 $/KWh) than that of the base case scenario (0.0043$/kWh) and 20 KW wind turbine case (0.012 $/KWh). The time that the ship uses the wind turbine is small (only one quarter of the year) and the price of installation and maintenance of the hybrid system is very big compared with the other cases. This is because the output power of the wind turbine exceeds the load demand and the effective use of the hybrid system. The impact of the power of the wind turbine on the internal rate of return, payback period and cost of energy savings (for the three cases mentioned before) are represented in Figures 15,16, and 17.
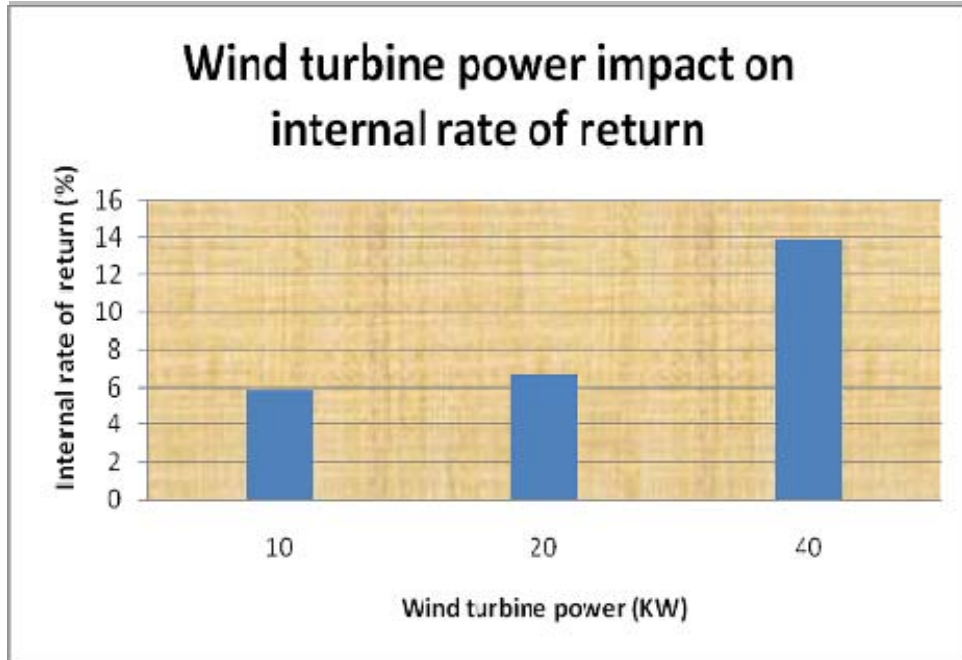
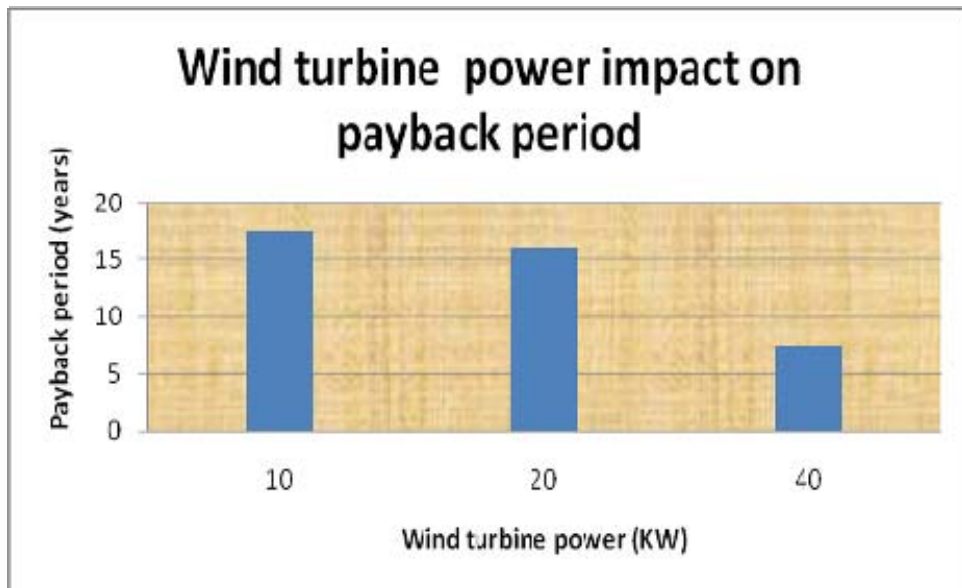**Figure 15.   Internal rate of return for three different power wind turbines**

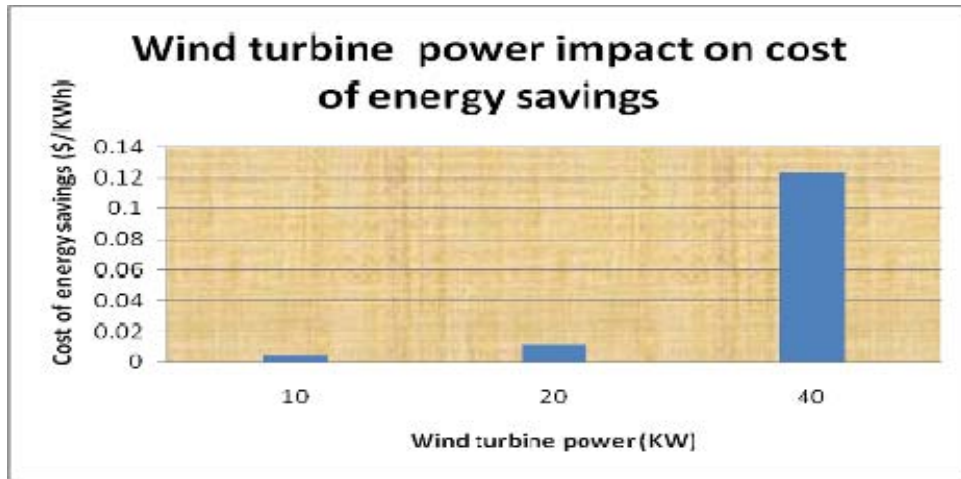**Figure 16.   Payback period for three different power wind turbines**

Figure 17.   Cost of energy savings for three different power wind turbines.

4.   Different Operational Scenario

In the base case above, it is assumed that it has a specific operational scenario. This operational scenario is a variable that depends upon different parameters, such as the area that the ship is protecting; the geographical site of this area; the distance between this area and enemy territories, etc. By changing the ship's operational scenario, the time that the ship stays in the harbors and, consequently, the time that the ship uses the wind turbine, changes, too. Three different operational scenarios will be examined and compared to the base case scenario. The input parameters are the same as the base case except that the yearly load and wind speed data is different for each operational scenario.

5.   Operational Scenario A

In the first operational scenario, the ship stays at the naval base about one third of the year; travels about two months within a specific area; and stays about half a year at the three harbors chosen on a yearly basis. Table 18 presents the output of the simulation program.

Yearly load demand (KWh)	196,829
Yearly energy generated by wind turbine (KWh)	8,774.9
Yearly energy generated by diesel (KWh)	188,055
Yearly dump energy (KWh)	29.2
Yearly fuel consumed by hybrid system (l)	66,998
Yearly fuel saved by hybrid system (l)	1,819.8
Diesel #1 operating hours (h)	5,856
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/KW)	3,714
Useful System life (years)	25
Fuel cost ($/l)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per liter consumed ($/l)	2.984
Payback Period (years)	11.22
Cost of energy for hybrid system ($/kWh)	1.043
Cost of energy for diesel-only system ($/kWh)	1.056
Internal rate of return (%)	10.291

Table 18.   Operational scenario A results.

When comparing these results to the base case scenario, the economic savings are satisfactory. The payback period of the system is reduced to about eleven years; the internal rate of return is increased to 10.291%; and the cost of energy savings, compared with the diesel-only case, is bigger (0.013 $/KWh) than that of the base case scenario (0.0043$/KWh). The reason is that the ship stays in the harbors more and, thus, can benefit more from the use of the wind turbine. This scenario is possible if the ship should spend more time at the islands.

6.   Operational Scenario B

In the second operational scenario, the ship stays at the naval base for about two months of the year; travels about two months within a specific area; and stays about eight months at the three harbors chosen on a yearly base. Table 19 presents the output of the simulation program.

Yearly load demand (KWh)	232,843
Yearly energy generated by wind turbine (KWh)	12,434.6
Yearly energy generated by diesel (KWh)	220,409
Yearly dump energy (KWh)	43.3
Yearly fuel consumed by hybrid system (l)	78,320.7
Yearly fuel saved by hybrid system (l)	2,578.5
Diesel #1 operating hours (h)	7,296
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/KW)	3,714
Useful System life (years)	25
Fuel cost ($/l)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per liter consumed ($/l)	2.984
Payback Period (years)	7.9
Cost of energy for hybrid system ($/KWh)	1.027
Cost of energy for diesel-only system ($/KWh)	1.0485
Internal rate of return (%)	14.378

Table 19.   Operational scenario B results.

Comparing these results to the base case and the first case scenario, the economic savings are bigger. The payback period of the system is reduced to about eight years; the internal rate of return is increased to 14.378%; and the cost of energy savings compared

to the diesel-only case is bigger (0.0215 $/KWh) than that of the base case scenario (0.0043$/KWh). The reason is that the ship stays in the harbors more and, thus, can benefit more from the use of the wind turbine. The chances of this scenario occurring are less, but not impossible, if the ship would spend more time at the island.

7.   Operational Scenario C

In the third operational scenario, the ship does not stay at the naval base; travels about two months within a specific area; and stays about ten months at the three harbors chosen on a yearly base. Table 20 presents the output of the simulation program.

Yearly load demand (KWh)	269,400
Yearly energy generated by wind turbine (KWh)	15,185.6
Yearly energy generated by diesel (KWh)	254,258
Yearly dump energy (KWh)	43.7
Yearly fuel consumed by hybrid system (l)	90,029.5
Yearly fuel saved by hybrid system (l)	3,152.1
Diesel #1 operating hours (h)	8,760
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/KW)	3,714
Useful System life (years)	25
Fuel cost ($/l)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per liter consumed ($/l)	2.984
Payback Period (years)	6.46
Cost of energy for hybrid system ($/KWh)	1.0186
Cost of energy for diesel-only system ($/KWh)	1.0426
Internal rate of return (%)	17.07

Table 20.   Operational scenario C results.

When comparing these results with all the other cases, the economic savings are the biggest in this case. The payback period of the system is reduced to about six and a half years; the internal rate of return is increased to 17.07%; and the cost of energy savings compared to the diesel-only case is the biggest (0.024 $/KWh) than any other case scenario. The reason is that the time that the ship stays at the islands and the amount of wind turbine have been maximized. This scenario is possible when an island is the naval base of the ship. The impact of the operational scenario on the internal rate of return, payback period and cost of energy savings (for the four cases mentioned before) are represented in Figures 18, 19, and 20.
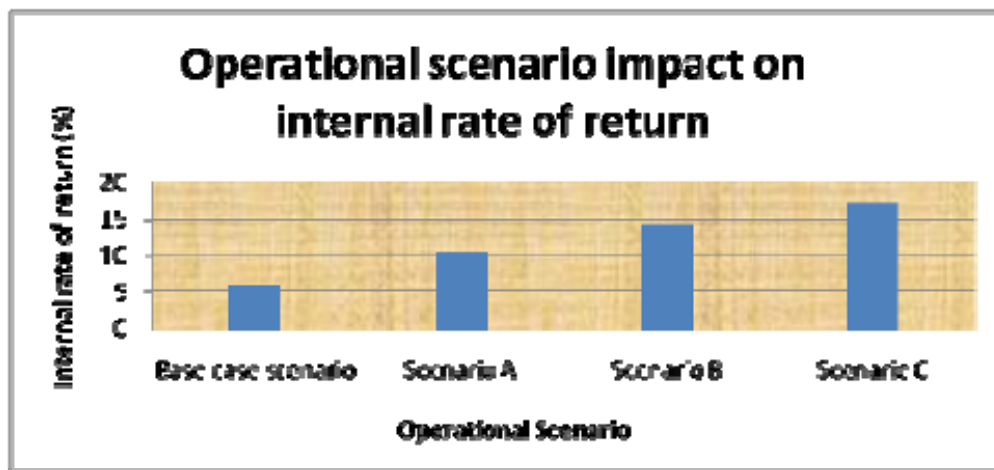

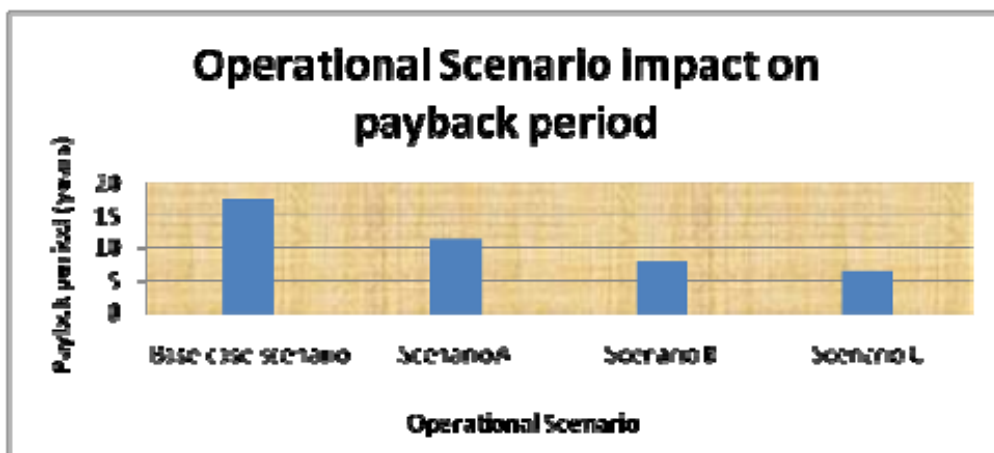**Figure 18.   Internal rate of return for four different operational scenarios.**

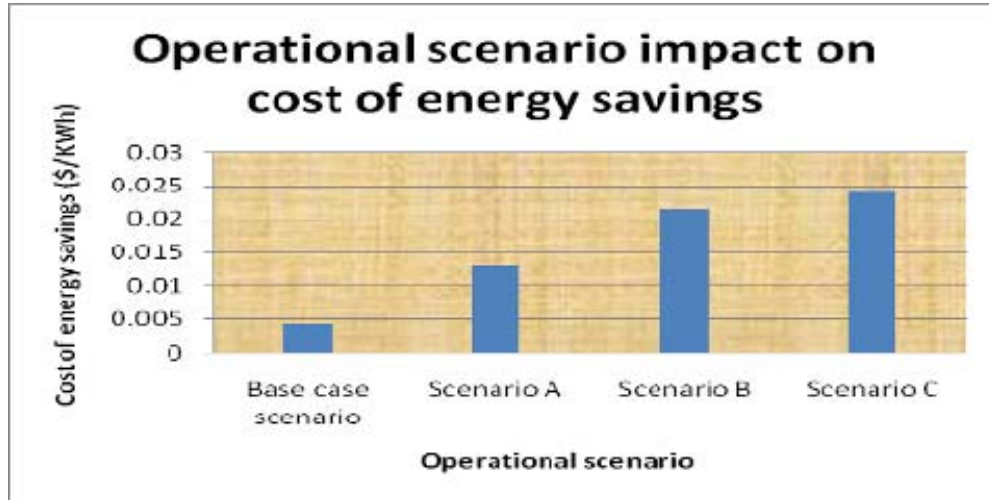**Figure 19.   Payback period for four different operational scenarios.**

Figure 20.   Cost of energy savings for four different operational scenarios.

8.   Decrease in the Cost of Wind Energy ($/KWh)

The unpredictable rise in the price of oil combined with environmental concerns has made the demand for use of wind power energy urgent. The law of the markets says, however, that if the demand increases, the cost decreases. Therefore, it is a logical assumption to expect that the costs of installation, operation, and maintenance of wind turbines would fall. Two different prices at the cost of wind energy are going to be examined below and compared to the base case scenario. The input parameters are the same as the base case scenario except for the cost of energy.

9.   Cost of Wind Energy 3000 $/KWh

In the base scenario, the cost of wind energy has been decreased to 3000 $/KWh from 3714 $/KWh. Table 21 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	3,000
Useful System life (years)	25
Fuel cost ($/lt)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per lt consumed ($/lt)	2.984
Payback Period (years)	14.59
Cost of energy for hybrid system ($/kWh)	1.061
Cost of energy for diesel only system ($/kWh)	1.068
Internal rate of return (%)	7.617

Table 21.   Cost of wind energy 3000$/KWh results.

When comparing these results to the base case scenario, the economic savings are slightly better. The payback period of the system is reduced to about fourteen and a half years; the internal rate of return is increased to 7.617% ; and the cost of energy savings compared to the diesel-only case is bigger (0.007 $/KWh) than that of the base case scenario (0.0043$/KWh). Since the price reduction of wind energy in this case is not big enough and the major parameter for economic savings is fuel, the earnings are not enough.

10. Cost of Energy 2500 $/KWh

In the second case, the cost of energy has been decreased to 2500 $/KWh from 3714 $/KWh in the base scenario. Table 22 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	2,500
Useful System life (years)	25
Fuel cost ($/lt)	1.82
Fuel inflation rate (%)	5
Levelized annual fuel cost per lt consumed ($/lt)	2.984
Payback Period (years)	12.42
Cost of energy for hybrid system ($/kWh)	1.06
Cost of energy for diesel only system ($/kWh)	1.068
Internal rate of return (%)	9.225

Table 22. **Cost of wind energy 2500 $/KWh results.**

When comparing these results to the previous case and the base case scenario, the economic savings are better. The payback period of the system is reduced to about twelve and a half years; the internal rate of return is increased to 9.225%; and the cost of energy savings compared to the diesel-only case is bigger (0.008 $/KWh) than that of the previous cases. The earnings, however, are not enough. This is because the cost of energy does not have any influence upon the fuel parameter. The impact of the installed cost on the internal rate of return, payback period, and cost of energy savings (for the three cases mentioned) are represented in Figures 21, 22, and 23.
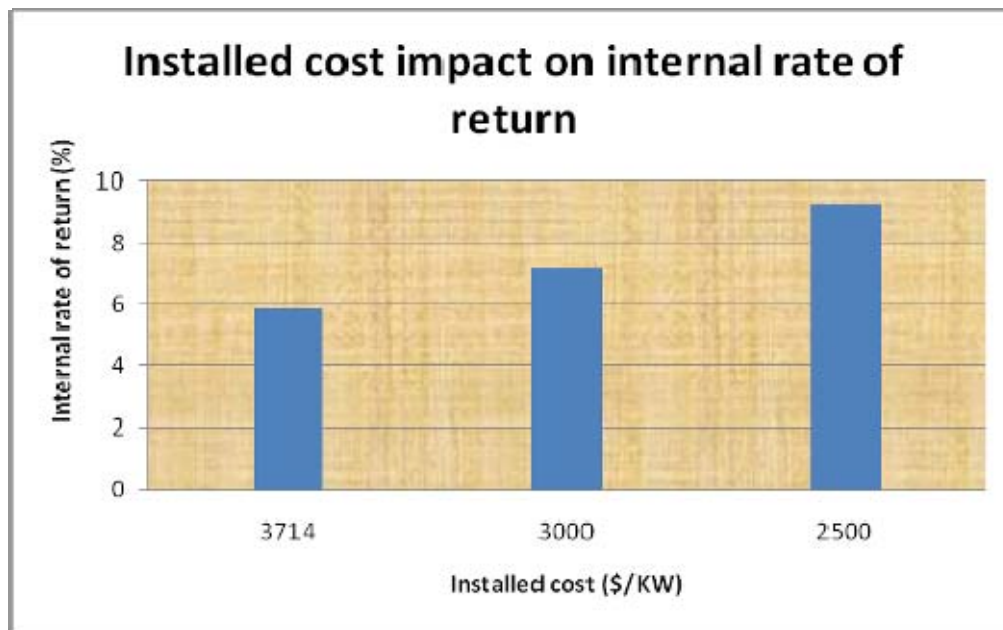
Figure 21.   Internal rate of return for three different cases of installed cost.
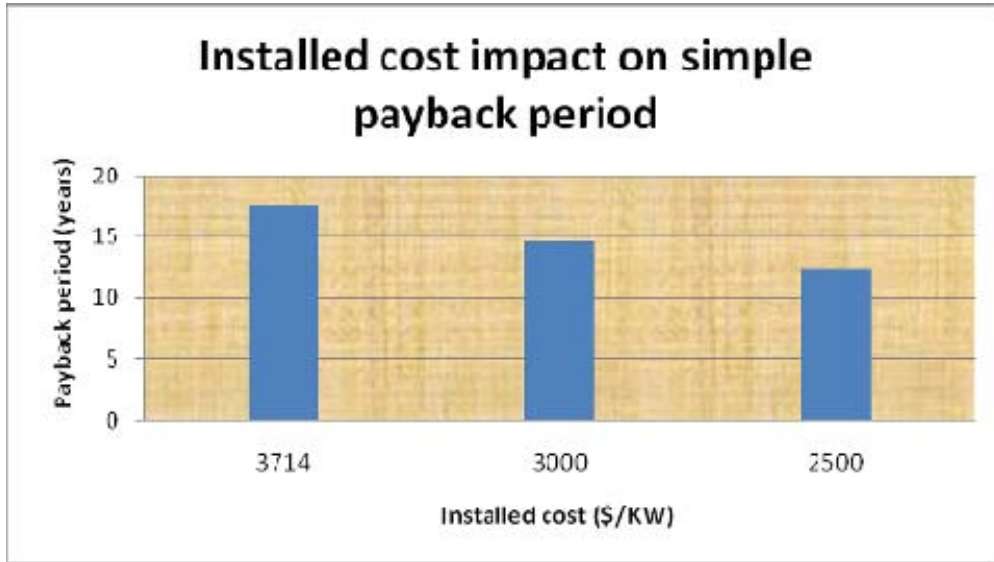
Figure 22.   Payback period for three different cases of installed cost.
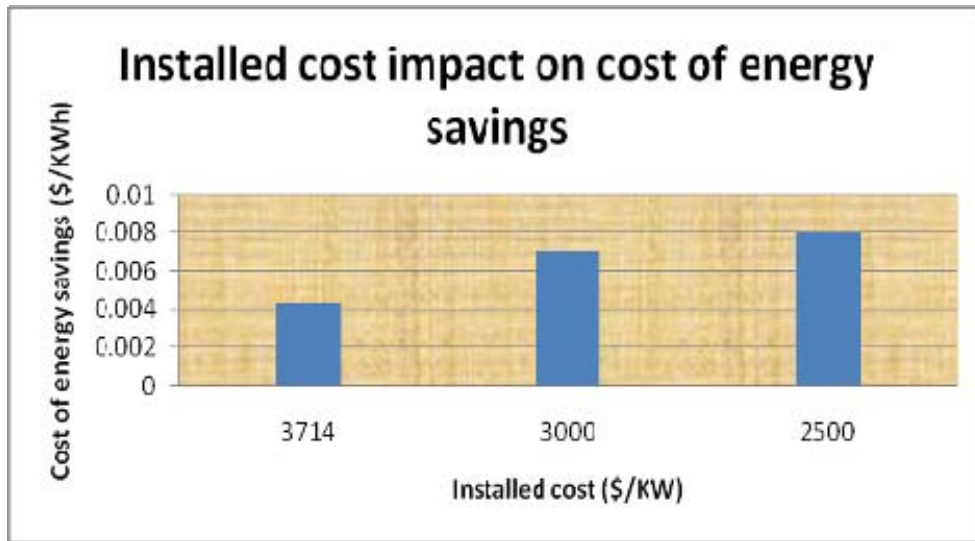
Figure 23.   Cost of energy savings for three different cases of installed cost.

11.   Increase in the Price of the Fuel

The price of fuel differs from country to country and from area to area within the same country. It is also unpredictable to make an assumption for future price even if that prediction was for next year. Three different fuel prices will be examined below and

compared to the base case scenario. All the other input parameters are the same as the base case scenario except for the price of fuel.

12. Price of Fuel 2.5$/Liter

In the first case, the price of fuel has been increased to 2.5$/liter from 1.82$/liter in the base case. Table 23 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	3,714
Useful System life (years)	25
Fuel cost ($/lt)	2.5
Fuel inflation rate (%)	5
Levelized annual fuel cost per lt consumed ($/lt)	4.099
Payback Period (years)	12.51
Cost of energy for hybrid system ($/kWh)	1.449
Cost of energy for diesel only system ($/kWh)	1.462
Internal rate of return (%)	9.124

Table 23.   Price of fuel 2.5$/liter results.

When comparing these results to the base case scenario, the economic savings are better. The payback period of the system is reduced to about twelve and a half years; the

internal rate of return is increased to 9.124%; and the cost of energy savings compared to the diesel-only case is bigger (0.013 $/KWh) than that of the base case scenario (0.0043$/KWh). The earnings are enough. This is because the fuel price is one of the most important parameters competing with the cost of the energy of the wind turbine.

13. Price of Fuel 3$/Liter

In the second case, the fuel price has been increased to 3$/liter from 1.82$/liter in the base case. Table 24 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	3,714
Useful System life (years)	25
Fuel cost ($/lt)	3
Fuel inflation rate (%)	5
Levelized annual fuel cost per lt consumed ($/lt)	4.919
Payback Period (years)	10.33
Cost of energy for hybrid system ($/kWh)	1.732
Cost of energy for diesel-only system ($/kWh)	1.751
Internal rate of return (%)	11.156

Table 24.   Price of fuel 3$/liter results.

Comparing these results with the previous case and the base case scenario, the economic savings are better. The payback period of the system is reduced to about ten and a half years; the internal rate of return is increased to 11.156%; and the cost of energy savings compared with the diesel-only case is bigger (0.019 $/KWh). This big increase at the price of fuel has increased the earnings significantly.

14.   Price of Fuel 4$/Liter

In the third case, the price of fuel has been increased to 4$/liter from of 1.82$/liter in the base case. Table 25 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	3,714
Useful System life (years)	25
Fuel cost ($/lt)	4
Fuel inflation rate (%)	5
Levelized annual fuel cost per lt consumed ($/lt)	6.559
Payback Period (years)	7.67
Cost of energy for hybrid system ($/kWh)	2.299
Cost of energy for diesel-only system ($/kWh)	2.33
Internal rate of return (%)	14.695

Table 25.   Price of fuel 4$/liter results.

When comparing these results to the previous cases, the economic savings are the largest. The payback period of the system is reduced to about seven and a half years; the internal rate of return is increased to 14.695%; and the cost of energy savings compared to the diesel-only case is the biggest (0.031 $/KWh). Such an increase in the fuel price difficult, but not impossible. In this case, the installation of a wind turbine is vital to minimize the fuel cost. The impact of the fuel cost on the internal rate of return, payback period and cost of energy savings (for the four cases mentioned before) are represented in Figures 24, 25, and 26.
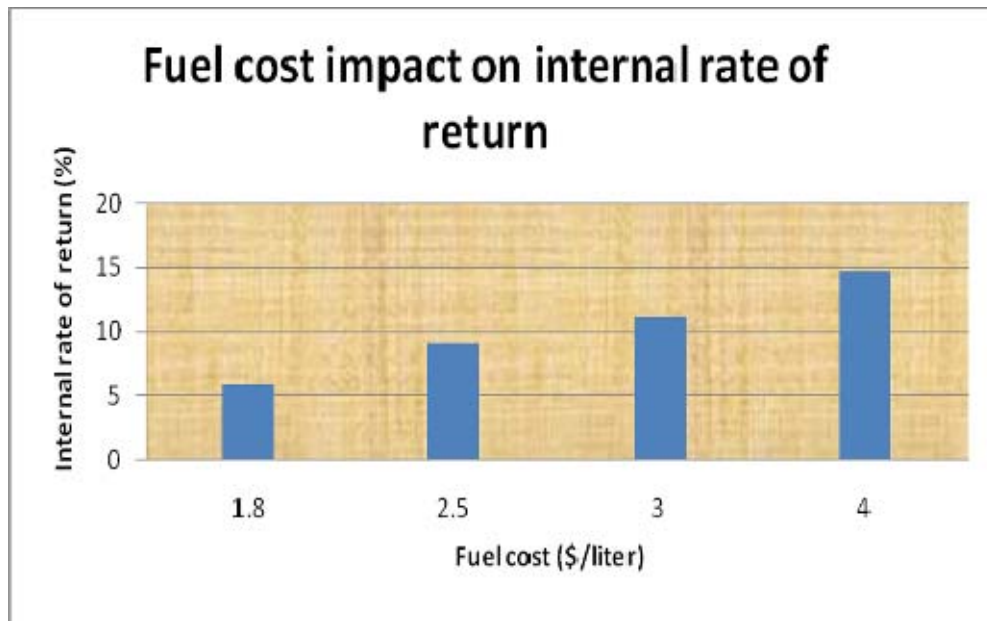

Figure 24.   Internal rate of return for four different cases of fuel cost.
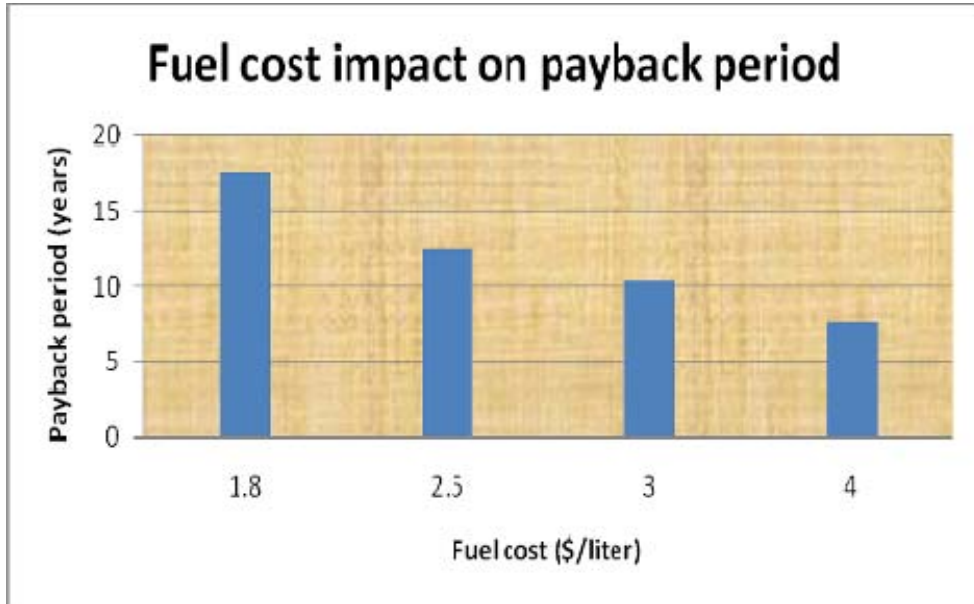
Figure 25.   Payback period for four different cases of fuel cost.

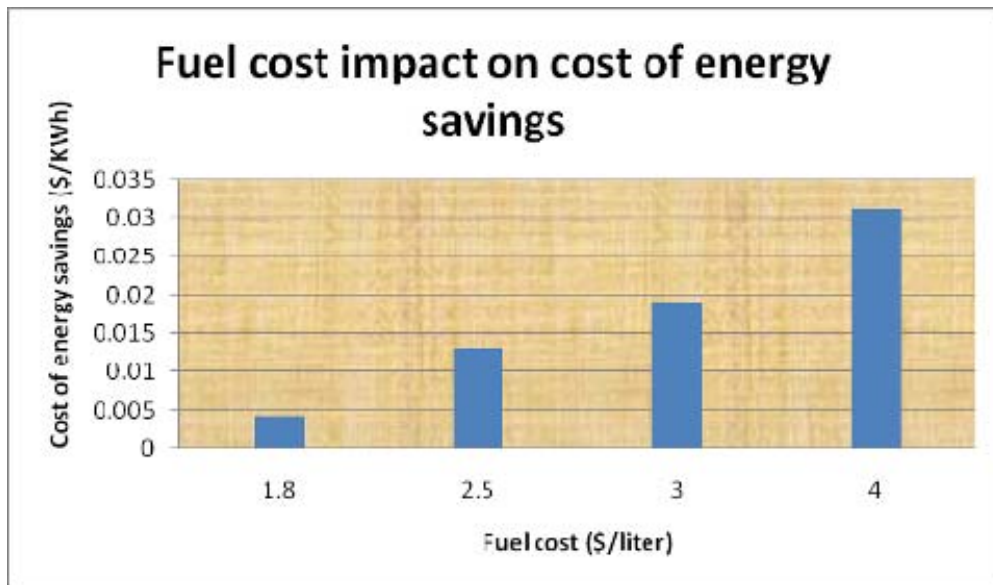**Figure 26.   Cost of energy savings for four different cases of fuel cost.**

15.   Increase in the Inflation Rate of the Fuel

Except for the price of fuel, the way that the price varies from year to year is unpredictable. Worldwide, certain and uncertain facts can lead to the inflation rate of fuel. Two different increases at the inflation rate of the fuel will be examined below and

compared to the base case scenario. All the other input parameters are the same as the base case scenario except for the inflation rate of fuel.

16.   Inflation Rate of the Fuel 10%

In the first case, the inflation rate of fuel has been increased to 10% from 5% of the base case. Table 26 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	3,714
Useful System life (years)	25
Fuel cost ($/lt)	1.82
Fuel inflation rate (%)	10
Levelized annual fuel cost per lt consumed ($/lt)	5.34
Payback Period (years)	12.42
Cost of energy for hybrid system ($/kWh)	1.877
Cost of energy for diesel-only system ($/kWh)	1.9
Internal rate of return (%)	11.673

Table 26.   Inflation rate of the fuel 10% results.

When comparing these results to the base case scenario, the economic savings are better. The payback period of the system is reduced to about twelve and a half years; the

internal rate of return is increased to 11.673%; and the cost of energy savings compared to the diesel-only case is bigger (0.023 $/KWh) than that of the base case scenario (0.0043$/KWh). This is because the price of fuel constantly increases on a yearly basis, which steadily increases profits of the wind turbine system.

17. Inflation Rate of the Fuel 15%

In the second case, the inflation rate of fuel has been increased to 15% from 5% in the base case. Table 27 presents the output of the simulation program.

Yearly load demand (kWh)	160,800
Yearly energy generated by wind turbine (kWh)	5,654.3
Yearly energy generated by diesel (kWh)	155,157
Yearly dump energy (kWh)	11.6
Yearly fuel consumed by hybrid system (lt)	55,563.6
Yearly fuel saved by hybrid system (lt)	1,173.3
Diesel #1 operating hours (h)	4,416
Diesel #2 operating hours (h)	1,440
Diesel #3 operating hours (h)	1,440
Diesel #4 operating hours (h)	0
Total system installed cost ($/kW)	3,714
Useful System life (years)	25
Fuel cost ($/lt)	1.82
Fuel inflation rate (%)	15
Levelized annual fuel cost per lt consumed ($/lt)	10.327
Payback Period (years)	9.85
Cost of energy for hybrid system ($/kWh)	3.601
Cost of energy for diesel-only system ($/kWh)	3.659
Internal rate of return (%)	17.137

Table 27.   Inflation rate of the fuel 15% results.

When comparing these results to the base case scenario and the previous scenario, the economic savings are the biggest. The payback period of the system is reduced to about ten years; the internal rate of return is increased to 17.137%; and the cost of energy savings compared to the diesel-only case is biggest (0.058 $/KWh). This is because the fuel price increases rapidly on a yearly basis, which increases profits when using the wind turbine in the same way. The impact of the fuel inflation rate on the internal rate of return, payback period, and cost of energy savings (for the three cases mentioned before), are represented in Figures 27, 28, and 29.

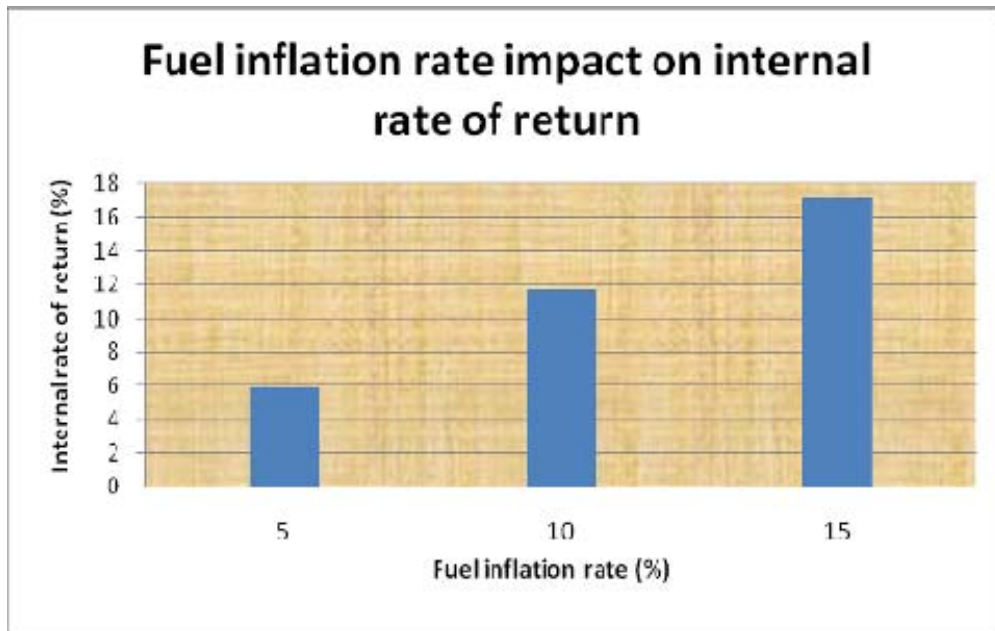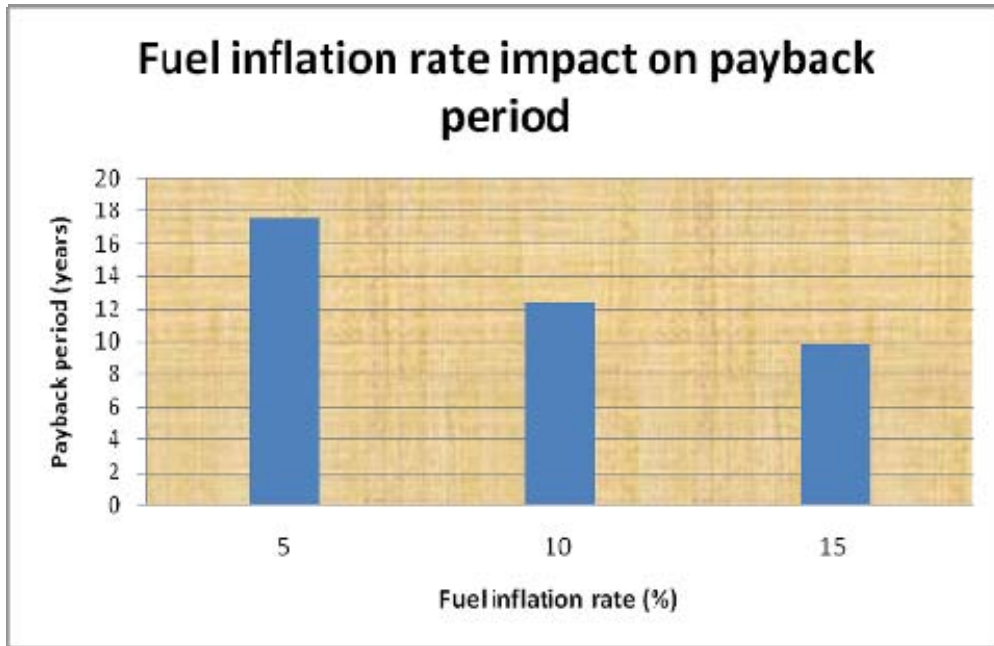**Figure 27.   Internal rate of return for different cases of fuel inflation rate.**

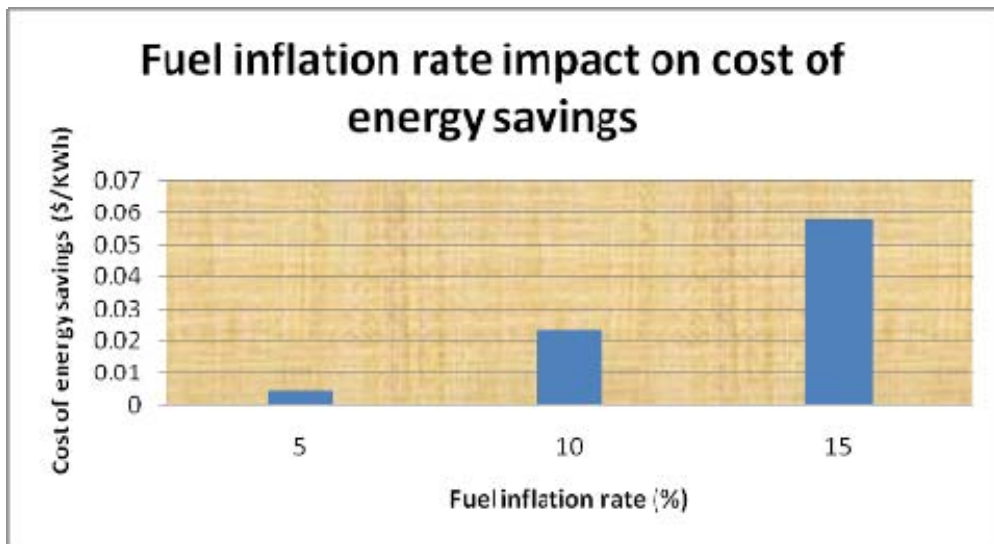**Figure 28.   Payback period for different cases of fuel inflation rate.**

Figure 29.   Cost of energy savings for different cases of fuel inflation rate.

F.   CONCLUSIONS

According to the results in each case demonstrated above, the following conclusions are presented:

-The annualized fuel cost per liter consumed ($/liter) depends only on the price and the inflation rate of fuel. The maximum price is 10.327 $/liter when the fuel inflation rate is 15%.

-The cost of energy ($/KWh) in the diesel-only case depends upon the fuel price, the inflation rate, and the operational scenario. The maximum price is 3.659 $/KWh when the fuel inflation rate is 15%.

-The cost of energy ($/KWh) in the hybrid system varies in all the cases mentioned above. In the case of the 40 KW wind turbine and the use of the hybrid system, it has a minimum value of 0.945 $/KWh. In the case of fuel inflation rate 15%, it has the maximum value of 3.601 $/kWh.

-The economic savings ($/KWh), comparing the cost of energy in the hybrid system ($/KWh) to the cost of energy in the diesel-only system ($/KWh), are biggest in the case of the 40 KW wind turbine having the maximum value of 0.123 $/KWh.

-The shortest payback period is 6.46 years in the case of operational scenario 3. In this case, the installed cost for the system is low and the ship uses the wind turbine all year. Therefore, to minimize the payback period, the installed cost of the system should be as low as possible and the wind turbine should be used for as long as possible.

-The internal rate of return (%) has the maximum value of 17.137 % in the case of a fuel inflation rate of 15 %. There is also a close value of 17.07 % in the case of operational scenario 3.

-The value of the installed cost of the system ($/KWh) does not greatly influence the economic savings compared to other parameters. This is because this is the initial cost paid in present time and not a recurring cost throughout the lifetime of the system.

-The operational scenario greatly influences system profits. The operational scenario with minimum ship travel time and maximum time staying in the harbors yields the biggest economic profits.

-The installation of the whole hybrid system is profitable when the wind turbine output power is more than the power demand of the load (excess energy). In this case, the hybrid system utilizes the wind power in the best way. This reduces the consumption of fuel by the diesel generators. The earnings for this reduction overcome the increased cost of the components' installation of the hybrid system and the recurring cost of battery replacement and bi-directional inverter at specific intervals throughout the lifetime of the system.

-Increases of fuel prices ($/liter) or the fuel inflation rate (%) also have a big influence on the economic savings of the system. Even though the total yearly fuel consumption savings by the hybrid system may be small, the increased value of these parameters makes earnings significant. An increase in fuel price also influences the payback period more when compared to an increased value of the inflation rate. When the increased value of inflation rate influences greatly, the opposite phenomenon occurs with the internal rate of return (%).

All the different cases being mentioned in the sensitivity analysis chapter and the economic outputs are illustrated in the Table 28.

	Payback Period (years)	COE ($/KWh) Hybrid	COE ($/KWh) Diesel	Internal rate of return (%)	Levelized annual fuel cost per liter consumed ($/liter)
Base Case	17.53	1.0637	1.068	5.875	2.984
Scenario A	11.22	1.043	1.056	10.291	2.984
Scenario B	7.9	1.027	1.0485	14.378	2.984
Scenario C	6.46	1.0186	1.0426	17.07	2.984
Fuel cost 2.5$/liter	12.51	1.449	1.462	9.124	4.099
Fuel cost 3$/liter	10.33	1.732	1.751	11.156	4.919
Fuel cost 4$/liter	7.67	2.299	2.33	14.695	6.559
Fuel inflation rate 10%	12.42	1.877	1.9	11.673	5.34
Fuel inflation rate 15%	9.85	3.601	3.659	17.137	10.327
Installed cost 2500$/KW	12.42	1.06	1.068	9.225	2.984
Installed cost 3000$/KW	14.59	1.061	1.068	7.617	2.984
20 KW wind turbine	16.08	1.056	1.068	6.637	2.984
40 KW wind turbine	7.53	0.945	1.068	13.842	2.984

Table 28.   Economic outputs of all the cases.

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VIII. NAVAL ARCHITECTURE CALCULATIONS

The installation on a ship of both a wind turbine and the hybrid system will modify the naval architecture characteristics of the ship. Extra weight will be added due to the weight of the hybrid system components. This weight will impact the new naval architecture ship performance. This impact should be studied. All these parameters are calculated below as a final step in deciding the degree of profits from the installation of the hybrid system on the ship.

A. INITIAL SHIP NAVAL ARCHITECTURE CHARACTERISTICS

First, the naval architecture characteristics of the ship before the installation of the hybrid system must be determined. These are needed to compare them to the final outputs after the installation of the hybrid system. The assumption is that the ship is full of fuel, oil, fresh water, and it is ready for battle. This data is known as the design data of the ship and it is shown in the Table 29.

Overall length (m)	55
Length between perpendicular, L_{BP} (m)	51
Overall width , B (m)	10.5
Displacement, D (T)	515
Mean draft, T_M (m)	2.54
Depth at forward perpendicular T_F (m)	2.55
Depth at backward perpendicular T_A (m)	2.53
Trim (m)	0.017 (toward the bow)
KG (m)	3.75
GM (m)	2.34
LCB (m)	24.01
LCG (m)	24.05
MCT/1m (tm/m)	1,180
TP/1 m (t/m)	383
LCF (m from AP)	21.16
KM (m)	6.095
KB (m)	1.5

Table 29.　　Initial naval architecture data of the ship.

B.　　HYBRID SYSTEM DATA CALCULATIONS

The base case consists only of the wind turbine of 10 KW and the necessary electronic devices (transformers, power electronics, etc.). This is to allow connection with the AC bus of the ship and to satisfy stability and proper cooperation between output voltage and frequency of the wind turbine and bus.

Since these electronic devices have negligible weight compared to the displacement of the ship, they will be ignored in these naval architecture calculations. Therefore, only the wind turbine data will be used to estimate the new naval architecture characteristics of the ship according to the Table 30.

Component	Weight (KG)	Dimensions (W*H*D cm)
Wind turbine Westwind 10KW with electric hydraulic tower	1,280	Tower: 8 m height

Table 30.   Weight and dimensions calculations of the wind turbine.

According to the calculations in the above table, the installation of the wind turbine will increase the weight of the ship of about 0.248 % compared to the initial one.

C.   INSTALLATION AND STORAGE OF THE HYBRID SYSTEM

The purpose of the installation of the wind turbine is to use it when the ship is away from its naval base and does not travel. In this case, the wind turbine will stand up on the main deck at the bow and before the separation point. When the ship travels, however, it must be placed down on the main deck and the generator should be properly covered to avoid damage and corrosion of the wind turbine from exposure to environmental conditions. Due to the weight of the generator, it would be difficult to carry and storage it in a compartment inside the ship. Thus, this study excludes it.

Except for the wind turbine, the necessary electronic devices (transformers, power electronics, etc.) should always be placed inside a compartment on the ship. To keep installing costs (wiring, losses, etc.) as low as possible, this compartment should be close to the wind turbine. The compartment exactly under the installation of the wind turbine on the main deck is the appropriate place to install all these electronic devices.

D. NAVAL ARCHITECTURE CHARACTERISTICS AFTER THE INSTALLATION OF THE HYBRID SYSTEM WHEN THE WIND TURBINE LIES ON THE DECK

At this point, the new naval architecture characteristics with the wind turbine lowered on the main deck will be calculated. It is assumed that the wind turbine weight is loaded symmetrically to the centerline. The purpose of this is for the effects that caused the off-center weight to the angle of heel will be neglected.

1. Displacement of the Ship

The new displacement of the ship is the addition of the initial displacement of the ship and the wind turbine weight. Therefore, it is:

$$D' = D + W = 515 + 1.28 = 516.28 ton \tag{19}$$

2. Center of Gravity

First, the vertical and the longitudinal center of gravity for the wind turbine should be calculated. Then, the new vertical and the longitudinal center of gravity for the whole ship would be calculated.

The vertical center of gravity for the wind turbine is:

$$KG_w = d_w + d_k = 0.6 + 6.5 = 7.1 \text{ m} \tag{20}$$

where:

d_w: height of the base of the tower from the main deck,

d_k: height of the main deck from the kneel.

The longitudinal center of gravity for the wind turbine is:

$$LCG_w = d + \frac{(W_{TOWER} * KG_{TOWER} + W_{TURBINE} * KG_{TURBINE})}{W_{TOWER+TURBINE}} =$$
$$= 45 + \frac{(900*3) + (380*8)}{1280} = 49.484 m \tag{21}$$

d: distance of the base of the wind turbine from the aft.

Finally, the new vertical center of gravity after the installation of the hybrid system is:

$$KG' = \frac{(KG*D)+(W_w*KG_w)}{D'} = $$
$$= \frac{(3.75*515)+(1.28*7.1)}{516.28} = 3.758m \tag{22}$$

The new longitudinal center of gravity is:

$$LCG' = \frac{(LCG*D)+(W_w*LCG_w)}{D'} = $$
$$= \frac{(24.05*515)+(1.28*49.484)}{516.28} = 24.113m \tag{23}$$

3.   Mean Draft

The new mean draft of the ship is given by the equation:

$$TM' = TM + \frac{W}{TP} = 2.54 + \frac{1.28}{383} = 2.543m \tag{24}$$

4.   Vertical Shift of Center of Buoyancy

The center of buoyancy for the wind turbine is given by the equation:

$$KB'' = T_M + \frac{1}{2}\frac{W}{TP} = 2.54 + \frac{1}{2}\frac{1.28}{383} = 2.5416m \tag{25}$$

The vertical shift of center of buoyancy is given by the equation:

$$KB' = \frac{KB*D+KB''*W}{D+W} = \frac{1.5*515+2.5416*1.28}{516.28} = 1.5025m \tag{26}$$

5.   New Metacentric Radius

According to the initial naval architecture data of the ship, the initial metacentric radius is:

$$BM = KM - KB = 6.095 - 1.5 = 4.595 \text{ m} \tag{27}$$

The new metacentric radius is given by the equation:

$$B'M' = BM * \frac{D}{D+W} = 4.595 * \frac{515}{515+1.28} = 4.583m \tag{28}$$

6.   New Metacentric Height

The new metacentric height is given by the equation:

$$G'M' = KB' + B'M' - KG' = 1.5025 + 4.583 - 3.758 = 2.3275m \tag{29}$$

7.   New Fore and Aft Drafts

The imagined shift of weight from the center of flotation (at 21.16 m) is in magnitude and direction:

$$X_{SHIFT} = LCG' - LCF = 24.113 - 21.16 = 2.953m \tag{30}$$

toward the bow

The additional trim of the ship is:

$$t = \frac{W * X_{SHIFT}}{MCT} = \frac{1.28 * 2.953}{1180} = 0.0032m = 0.32cm \tag{31}$$

Then, the new fore and aft drafts are:

$$T_F' = T_F + \frac{W}{TP} + \frac{L_{BP}/2 + (L_{BP}/2 - LCF)}{L_{BP}} * t =$$
$$= 2.55 + \frac{1.28}{383} + \frac{51/2 + (51/2 - 21.16)}{51} * 0.0032 = 2.555m \tag{32}$$

$$T_A' = T_A + \frac{W}{TP} - \frac{L_{BP}/2 - (L_{BP}/2 - LCF)}{L_{BP}} * t =$$
$$= 2.53 + \frac{1.28}{383} - \frac{21.16}{51} * 0.0032 = 2.532 \tag{33}$$

E. NAVAL ARCHITECTURE CHARACTERISTICS AFTER THE INSTALLATION OF THE HYBRID SYSTEM WHEN THE WIND TURBINE IS STANDING UP ON THE MAIN DECK

A different situation exists when the wind turbine stands up on the main deck. The new naval architecture characteristics of the ship in this situation will be calculated. Except for the wind turbine, the other electronic components will be located in the same compartment as previously mentioned. The new naval architecture characteristics are the following:

1. Displacement of the Ship

The new displacement of the ship is the same as the previous case since the additional weight of the hybrid system remains the same. Therefore, it is:

$$D' = D + W = 515 + 1.28 = 516.28 ton \tag{34}$$

2. Center of Gravity

The vertical center of gravity for the wind turbine is:

$$
KG_w = d_k + \frac{(W_{TOWER} * KG_{TOWER} + W_{TURBINE} * KG_{TURBINE})}{W_{TOWER+TURBINE}} =
$$
$$
= 6.5 + \frac{(900*3) + (380*8)}{1280} = 10.984m \tag{35}
$$

The longitudinal center of gravity for the wind turbine is:

LCG$_w$=45m

Finally, the new vertical center of gravity is:

$$
KG' = \frac{(KG * D) + (W_w * KG_w)}{D'} =
$$
$$
= \frac{(515*3.75) + (1.28*10.984)}{516.28} = 3.767m \tag{36}
$$

Finally, the new longitudinal center of gravity is:

$$LCG' = \frac{(LCG*D)+(W_w*LCG_w)}{D'} =$$
$$= \frac{(24.05*515)+(1.28*45)}{516.28} = 24.101m \tag{37}$$

3. Mean Draft

The new mean draft of the ship is the same like the previous case, since the additional weight of the hybrid system remains the same.

$$TM' = TM + \frac{W}{TP} = 2.54 + \frac{1.28}{383} = 2.543m \tag{38}$$

4. Vertical Shift of Center of Buoyancy

The center of buoyancy for the hybrid system is the same as the previous case, since the additional weight of the hybrid system remains the same.

$$KB'' = T_M + \frac{1}{2}\frac{W}{TP} = 2.54 + \frac{1}{2}\frac{1.28}{383} = 2.5416m \tag{39}$$

The vertical shift of center of buoyancy is given by the equation:

$$KB' = \frac{KB*D+KB''*W}{D+W} = \frac{1.5*515+2.5416*1.28}{516.28} = 1.5025m \tag{40}$$

5. New Metacentric Radius

According to the initial naval architecture data of the ship, the initial metacentric radius is:

$$BM = KM - KB = 6.095 - 1.5 = 4.595 \text{ m} \tag{41}$$

The new metacentric radius is given by the equation:

$$B'M' = BM * \frac{D}{D+W} = 4.595 * \frac{515}{515+1.28} = 4.583m \tag{42}$$

6. New Metacentric Height

The new metacentric height is given by the equation:

$$G'M' = KB' + B'M' - KG' = 1.5025 + 4.583 - 3.767 = 2.3185m \qquad (43)$$

7. New Fore and Aft Drafts

The imagined shift of weight from the center of flotation (at 21.166 m) is, in magnitude and direction:

$$X_{SHIFT} = LCG' - LCF = 24.101 - 21.16 = 2.941m \qquad (44)$$

toward the bow

The additional trim of the ship is:

$$t = \frac{W * X_{SHIFT}}{MCT} = \frac{1.28 * 2.941}{1180} = 0.00319m = 0.319cm \qquad (45)$$

Then, the new fore and aft drafts are:

$$T_F' = T_F + \frac{W}{TP} + \frac{L_{BP}/2 + (L_{BP}/2 - LCF)}{L_{BP}} * t =$$
$$= 2.55 + \frac{1.28}{383} + \frac{51/2 + (51/2 - 21.16)}{51} * 0.00319 = 2.555m \qquad (46)$$

$$T_A' = T_A + \frac{W}{TP} - \frac{L_{BP}/2 - (L_{BP}/2 - LCF)}{L_{BP}} * t =$$
$$= 2.53 + \frac{1.28}{383} - \frac{21.16}{51} * 0.00319 = 2.532m \qquad (47)$$

F. DESIGN CONSIDERATIONS

According to the results above after the installation of the hybrid system, there will be a displacement of the ship equal with $D_{FINAL} = 516.28$ tons. Since the initial displacement of the ship was $D_{INITIAL} = 515$ tons, a weight of W=1.28 tons at the ship will be added. If the intent is to avoid this increase at the displacement of the ship, practical solutions must be designed. One solution would be to reduce the fuel storage capacity of the ship: for each 1.28 tons, subtract an equal amount of 0.64 ton from both the main

storage fuel tanks. This would decrease the total fuel capacity of the ship from 115 tons to 113.72 tons (1.113% in percent). Since this solution would not significantly decrease the operational strength of the ship, it is allowable. To reach the required difference displacement of 1.28 tons, other non-operational weights can also be reduced. Therefore, the conclusion is that we can continue with this increase at the total displacement. The difference in the naval architecture characteristics of the ship is small and does not really influence the stability of the ship.

IX. CONCLUSIONS AND RECOMMENDATIONS

Finally, as a result of this study, the following conclusions and recommendations can be drawn:

-Hybrid system is preferred in the case of excess power where the wind turbine output power exceeds the load demand.

-A good, realistic, and overall knowledge of the operational scenarios of the ship is of vital importance for the prediction of the earnings of the hybrid system.

-Since the power produced by a wind turbine is proportional to the third power of wind speed, a reliable prediction of prevailing wind characteristics is essential. A wind analysis of the regions that the wind turbine is going to be used should be conducted to correctly estimate the yearly output energy of the wind turbine.

-The installation and use of a wind turbine on the ship should not prevent the operational readiness of the ship, reduce survivability, or increase the probability of injury of the crew. Naval architecture characteristics and other restrictions of the ship should also be taken into account. Depending on the ship type, different wind turbines can be used. In each case, profit varies.

-The global trends towards increases in fuel price and the significant savings from the use of the wind turbine makes the installation of the wind turbine a necessity. Environmental concerns about the pollution of the environment also enhance the need.

-Finally, the fundamental assumption of keeping the turbine offline during ship travel may be revised. This is of course ultimately related to the mission of the ship. If mission effectiveness is not degraded by the presence of the turbine, even a smaller turbine will result in significantly higher savings. In cases where the ship is primarily stationed in open seas, such as seabasing applications, higher savings are also expected. This however, would have to be considered against reductions in the available deck space, which relates back to the primary mission of the ship.

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