

Technologies, Feasibility, and Management Strategies for On-Board Multi-Source Energy Networks

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Abstract— The paper discusses the feasibility of installing renewable energy generation technologies on sea-going transport, taking into account the additional weight and power consumption. This study is based on the power management of a 26,198 tonne commercial chemical tanker. The management system would aim at reducing the number of generators as well as the power required from burning fossil fuels. After a process of elimination of potential technologies based on feasibility of the project and shipboard application, the work is focused towards photovoltaic and wind energy generation in combination with fossil fueled engines and Li-ion battery storage covering the higher energy density needs, and the intermittent nature of renewables. The network architecture is optimized in order to have the highest efficiency, and reduced system weight. The results show that successful management of the system can lead to reduction in generator requirement, as well as fuel consumption and energy despite the weight of the extra installation.

Keywords—ship, energy management, renewable energy, solar, marine, storage

I. INTRODUCTION

With newer regulations on emission from marine transport coming into effect in certain parts of the world, the feasibility of harvesting renewable energy on-board marine vessels need to be carefully considered. Due to the portable nature of the application, the additional weight penalty of renewable system installation needs to be carefully studied and work is to be done in order to cover the gap between generation/storage technologies applied on-shore, against those that are suitable for portability and operate off-shore. This study will investigate the feasibility of powering the ship auxiliary systems of a commercial tanker whose specifications are given in Table 1 [1]. The auxiliaries may include pumps, blowers, coolers, compressors, vent fans, boilers, thrusters, hotel loads etc. A range of renewable energy technologies including wind and solar energy is considered to assess their suitability for

maritime applications. Harvesting energy from motion of the vessel due to wave energy has been considered but the power generated is deemed too small, from the mechanical devices that have been tested [2], and there has been no optimal technology for converting the kinetic energy from ship motions to electric energy yet. Calculations are made on solar and wind power profiles for representative days and locations, to be compared with the vessel's power profile. The results are used to find the best possible mix of energy storage and generation, with an aim to keep the cost and weight at a minimum. The unpredictable nature of energy generation from renewable sources calls for its combined operation with Energy Storage Systems (ESS) in order to optimally manage power from each unit. With the load demand, from e.g. maneuvering systems, auxiliary machinery, air conditioning etc. of tankers being more or less constant, spikes of instantaneous power demands are rare, and therefore the high energy density, slow discharging batteries will be considered for the system, with supercapacitor being a good supplement for transients.

In the rest of the paper, section II describes the different energy generation methods employed onboard the vessel supplementary to its existing diesel engines, and possible architectures of integrating them into the ship grid. Section III outlines the sizing of and energy capacities of each of the installed energy sources and storage systems based on the space constraints of the vessel. Section IV calculates the extra weight related consumption of the installed system and comments on its feasibility. Section V outlines the management of the overall system along with a control strategy to finally tie all the generation and storage devices in an effective arrangement.

II. ENERGY GENERATION METHODS

According to an amended report by DNV for Shipping 2020 [3], the uptake of hybrid systems in ship powering has been more rapid with batteries being placed in conjunction with fossil fueled engines resulting into a complex and efficient system of fuel mixture. Fig. 1 shows two alternative proposals for electrical power system architecture for the ship in relation to the energy storage system, as opposed to the conventional AC distribution. Fig. 1(a) contains a DC bus suitable for avoiding reactive power in high power levels and

TABLE 1: PHYSICAL AND ELECTRICAL SPECIFICATIONS OF TANKER

Length(m) x Breadth (m)		159.03 x 27.1	
Maximum Auxiliary Demand (kW)		1453	
Generator	No.	Prime Mover (kW)	Output (kW)
Main Generator	3	660	600

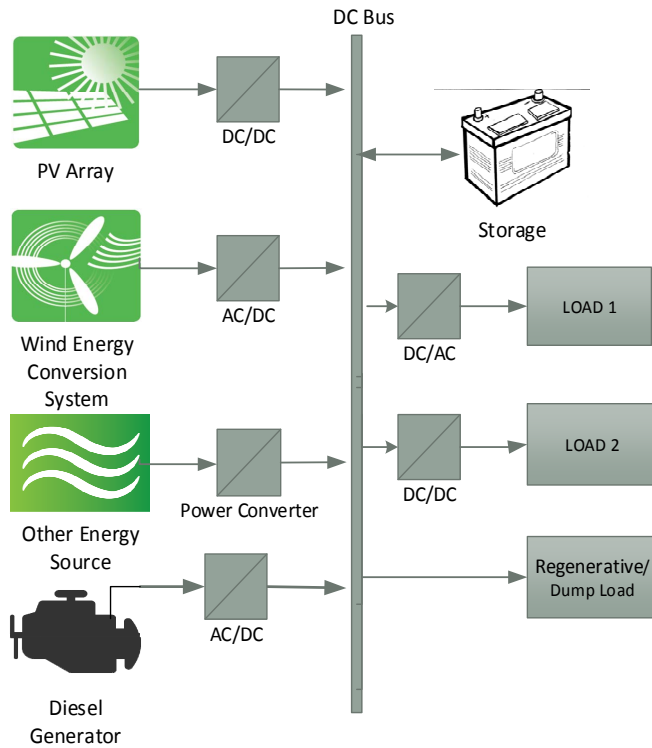


Figure 1a: Block diagram of potential multi-source renewable energy ship powering network

operating prime movers at optimal speed without the need for synchronization based on bus frequency, resulting in fuel savings. Space and weight saving due to the flexible arrangement of DC bus system has been reported in [4] and [5]. Fig. 1(b) incorporates a parallel AC/DC bus approach resulting into fewer conversion stages, and increased efficiency, resulting in further space and weight saving. The management strategy is to be optimized in various ways including number of inverters and hence their combined efficiency, voltage of bus, and therefore the appropriate wiring and safety measures, weight and volume.

The fastest developing green technology, namely solar power, will be investigated in more detail to meet ship auxiliary demand. A few projects have successfully integrated photovoltaics into ship power system with results of emission reduction, where some system configurations contribute to auxiliaries alone and others assist towards propulsion [6] [7] [8]. Different modes of operation of the PV arrangement can be addressed to identify the best possible network architecture when combined with the ship grid or operating stand-alone.

Wind turbines mounted on ships require adequate differential wind speed over the turbine rotors and the design of turbine blades may need some alterations to optimize ship performance in presence of energy from wind sources [9]. It is however possible to carry out initial estimation using the data and characteristics of available Horizontal Axis Wind Turbine (HAWT) in the market, along with the meteorological wind

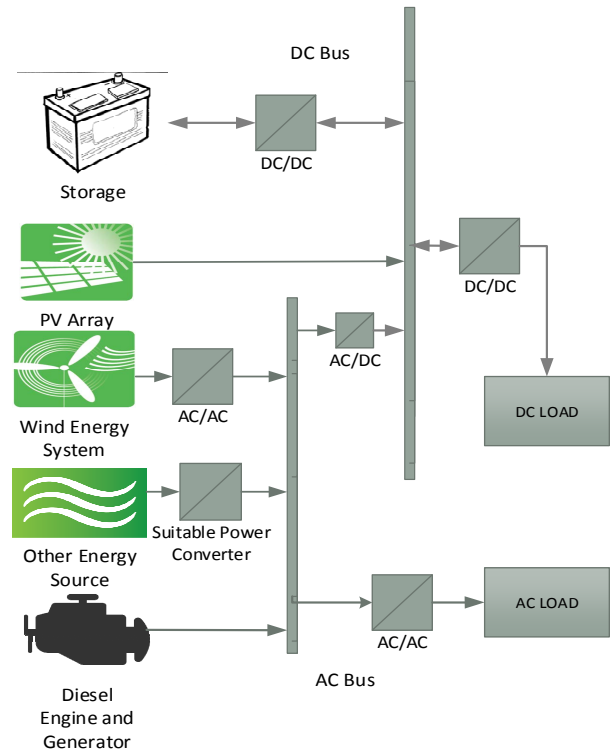


Figure 1b: Block diagram of alternative potential multi-source renewable energy ship powering network

speed data. The conclusions drawn in this study has utilized specifications of a market available HAWT.

For storage, Li-ion battery technologies are chosen due to their high energy-to-weight ratio and their ability to undergo intensive charge and discharge cycles. Table 2 compares the longevity, energy-density, and efficiency of different battery technology to highlight the best possible option [10] [11] [12] [13]. It has also been noted that Li-ion batteries have a learning curve with a gradient of 21% which means their cost have fallen by 21% for every doubling of production. Due to

TABLE 2: COMPARISON OF BATTERY TECHNOLOGY

Electro-chemistry	Cycle Life (No. of Full Discharge Cycles)	Calendar Life (years)	Monthly self-discharge at r.t.p. (%)	Energy Density (Wh/kg)	Cycle Efficiency (%)
Lead - acid	1200-1800	5-8	3-5	40	63-90
Lithium-ion	1500-2000	8-10	5-10	80-190	97
Sodium Battery	2500	15	~0	100	89-92%
Nickel-cadmium	1000-3000	10-15	20-30	50	72-78
Nickel-metal Hydride	1000-3000	8-10	20-30	80	66%
Flow Batteries	10,000	>20	~0	40-70	75-85

TABLE 3: PV ARRAY SIZING

Modules per string		Number of strings
Minimum	18	118
Maximum	25	85

their use outside grid, e.g. in electric vehicles and consumer items such as cell phones, the cost reduction for this technology of batteries has been faster and most prevalent hence likely to have further cost reductions in the future [14].

The network architecture and their integration into shipboard power system to supply an emission free powering option for the auxiliaries will be approached from a management perspective, since hybridization makes management more complex and diverse. Detailed energy management will be established through analyzing demand and availability of resources and imposing decision making algorithms on the operation scenarios of the network.

III. SIZING THE NEW SYSTEM

For the photovoltaic system, the capacity of PV installation is limited by the useable area of the ship while the power output is dependent on solar insolation at that particular location [15]. Assuming 50% space availability for solar panel installations, due to the shape of the ship not being rectangular and avoiding areas near the shade of cranes, flagstaff, and radar dome etc., an approximate top surface area of 2155 m² can be utilized. Marine grade solar panels available in the market have been considered, narrowing on the standard 135 Watt module having an area of 1.01 m² with each panel weighing about 10 kg. It is thereby calculated that approximately 23 tonnes of panels can be accommodated on-board. Considering 5 hours of peak average daily sunlight, the panels could produce up to 1438 kWh/day of energy. This can replace about 11% of auxiliary energy delivered by one 600 kW generator over a day.

The PV array is designed based on the known number of PV modules, with the minimum string length being enough to provide the required voltage to turn inverter ON and the maximum number providing lower voltage than maximum inverter input voltage. The following equations are used to determine the maximum and minimum number of modules for the array.

$$\text{Maximum number of modules per string} = \frac{V_{HI}}{V_{HM}} \quad (1)$$

$$V_{HM} = V_{OC} + V_{inc} \quad (2)$$

$$V_{inc} = -T_L \times \text{Temperature coefficient of } V_{OC} \quad (3)$$

Where, V_{HI} = maximum acceptable inverter voltage which can be found from inverter specifications, V_{HM} is the highest voltage expected from each module, T_L is the difference of lowest ambient temperature from STC, and the open-circuit voltage, V_{OC} at STC and its temperature coefficient is obtained from the specification of the solar panel used.

$$\text{Minimum number of modules per string} = \frac{V_{LI}}{V_{LM}} \quad (4)$$

$$V_{LM} = V_{MP} + V_{dec} \quad (5)$$

TABLE 4: PV AND WIND ENERGY CONVERSION SYSTEM SPECIFICATION

Area Available for Solar Panel Installation (m ²)	2155
No. of Panels	2130
Energy provided by PV over a day (MWh)	1.438
Wind Turbine Rated Power (kW)	85
No. of Turbines	8
Total Peak Power Provided (kW)	680
Combined weight of PV and Wind Installations (tonnes)	73

$$V_{Dec} = T_H \times \text{Temperature coefficient of } V_{OC} \quad (6)$$

Where, V_{LI} = minimum acceptable inverter voltage, V_{LM} is the lowest voltage expected from each module, T_H = difference of highest ambient temperature from STC, and the voltage of the module at maximum power, V_{MP} at STC is obtained from the specification of the solar panel used.

The array is finally designed with maximum allowed modules in series to allow lower current flowing for the same watts. Table 3 shows two extreme options for the series-parallel arrangement of PV modules. A series of 25 PV modules in 85 parallel strings thereby make up the array of 2125 modules on-board the tanker.

Eight 85 kW wind turbines are required to replace the peak power provided by one more 660 kW generator and would incur a further 50 ton to be added to the total weight of the ship. However, the excess energy requirement due to overcoming the drag force on a generic wind turbine system can significantly add to the value, unless specifically designed for ship-board application, which will be looked into detail at a later stage. The data for solar and wind energy system is summarized in Table 4.

The battery capacity must be determined from the maximum power deficit of the combined generation units in relation to load, which needs to be stored during generation for supplying at later times. It is therefore given by (7), where, P_{Gen} is the power supplied by the Diesel Generator Set, P_{PV} is the power generated by the PV Energy Conversion system, P_W is the power given by the wind energy conversion system, P_{dem} is

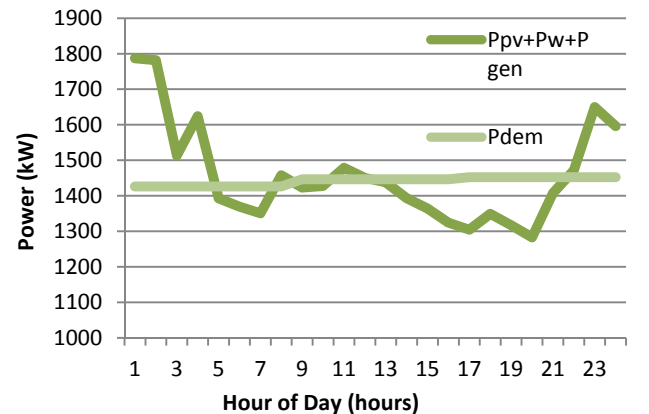


Figure 1: Generation and Load profile for Tanker while Cargo Unloading at Port

the power demanded by the ship.

$$P_{net} = P_{Gen} + P_{PV} + P_w - P_{dem} \quad (7)$$

$$P_{TOTAL} = P_{Gen} + P_{PV} + P_w + P_{Batt} \quad (8)$$

Each generator will come into use only when P_{TOTAL} , i.e. the combination of the renewable sources and stored energy, and the previous generator, is unable to supply load demand. Fig. 2 shows the load profile of the tanker under the condition of cargo handling at port, when demand is at a maximum. Without renewable energy systems, all three diesel generators would be running to meet the load demand, giving an output power of 1,800 kW. However with the help of wind and PV generated power, and that drawn from the battery during the deficit hours, it would be sufficient for the tanker to operate with only 2 diesel generators for auxiliary electrification, in place of 3.

From Fig. 2, the energy deficit during the 14th to 22nd hour of the day is highest and the battery can be sized according to this requirement calculated to be approximately 867.7 kWh. Considering 3 days of autonomy and 50% depth of discharge, the required battery capacity is calculated to be, 5.21 MWh. With 12 V battery cells available in the market, the combination of 2066 batteries of 210 Ah rating will be able to supply the demand. As a rule of thumb, the battery pack will be able to take as input C/5 or 1 kW, where C is the Battery capacity in Wh. The largest power peak during excess generation is 360 kW; therefore no further energy storage device is required to absorb this power. The average weight of 210 Ah batteries can be taken as 61 kg each, giving an equivalent total of 126 tonnes for the storage system, and volume equal to that of one 30 foot container.

The combined generation and storage system therefore total approximately 200 tonnes. When compared with a case study of an A-Type container ship [16], it is seen that Waste Heat Recovery (WHR) and Exhaust Gas Recirculation (EGR) systems, when retrofitted into ships to meet current regulations, can have weight penalty of up to 900 tons, which is far greater than installation of the renewables.

A. Extra Weight Related Consumption

A method is detailed for the estimation of extra energy input required to propel the ship owing to the additional resistance imposed by the weight of the new renewable energy system. The extra weight w incorporates the weight of the wind turbine system, solar panels and auxiliaries and battery storage system, less the weight of the third generator which is now redundant. Resistance which acts upon the ship comprises of three main divisions, namely the Frictional or Skin Resistance (R_f), Wave Resistance (R_w) and Air Resistance (R_a) [17]. R_f is the resistance due to the viscous stresses that the water exerts on the hull of the ship, R_w is caused by waves generated by the motion of the ship and R_a is resistance caused by the flow of air over the ship. There will be a slight reduction in R_a due to the amount of the hull that dips down into water; however this quantity is very small, about 2%, and therefore can be ignored [18]. The R_w is also more heavily dependent on the hull shape and speed of ship, over

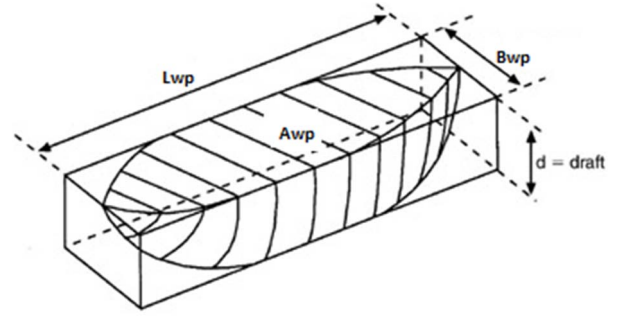


Figure 3: Ship dimension used for calculation of resistance

displacement, and therefore will not be looked into detail in this study considering the hull shape and speed remains constant for both scenarios [19]. For R_f , using the specified Tonnes per Inch (TPI) of the tanker, it is possible to find the increase in the draught of the ship, given by d , and thereby the surface area of the ship pushing through water [20].

$$d = \frac{w}{TPI} \quad (9)$$

$$TPI = \frac{\text{Weight to increase the draught one inch (LT)}}{1 \text{ in}} \quad (10)$$

$$\text{Or, } TPI = \frac{A_{wp}}{420} \left(\frac{LT}{in} \right) \quad (11)$$

Where A_{wp} is the water plane area in ft^2 , and is expressed by the following equation, in which, L_{wp} is the length of the water plane, B_{wp} is the hull's largest beam on water plane and C_{wp} is the water plane area coefficient, which is given as 0.95 for a typical tanker at an approximate cruise speed of 17 knots [21].

$$A_{wp} = C_{wp} \times L_{wp} \times B_{wp} \quad (12)$$

Putting the values in place, with L_{wp} of 147 m or 482 ft and the previous value for beam results in water plane area of 40590 ft^2 , TPI of 97.63 LT/in and $d = 2.07$ inch. After conversions into suitable units, this gives an increment of 7.96 m^2 in wetted surface area (A_s), giving rise to higher R_f , which in turn will result in greater fuel consumption for propulsion, given the speed V of the ship remains constant.

$$R_f = \frac{1}{2} \rho V^2 A_s \times C_f \quad (13)$$

Where C_f is specific frictional resistance coefficient and R_n is the dimensionless Reynold's number, given by the following equations [15] [19]. The kinematic viscosity of fluid, given by ν , varies according to temperature for a specific fluid. At an average 10°C, the kinematic viscosity of water is given as $1.307 \times 10^{-6} m^2/s$ [22].

$$C_f = \frac{0.075}{(\log R_n - 2)^2} \quad (14)$$

$$R_n = \frac{VL_{wl}}{\nu} \quad (15)$$

$$P_{ex} = R_f \times V \quad (16)$$

The resulting R_f is 467.3 N, which when multiplied by the speed of the ship gives the increase in effective towing power, P_{ex} , as 4089 W. Over a day, this equates to an added energy consumption of 98 kWh, which is much less in comparison to

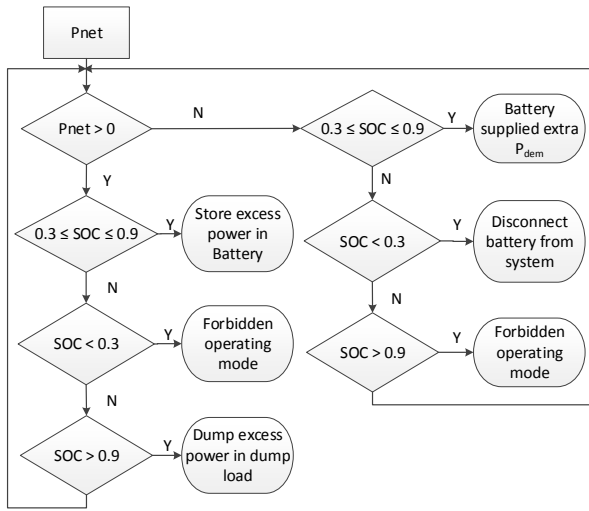


Figure 4: Flow Chart of Generation and Storage Management

the extra 6155 kWh of energy given by the combined renewable energy system.

IV. MANAGEMENT

With multiple energy sources such as diesel engine, fuel cells, solar and wind turbines integrated into providing shipboard power, the presence of ESS allows reliability and redundancy by collective usage and management of the sources. A control strategy has also been developed for the hybrid system, and different modes of operation are assigned depending on the generation and load discrepancies, as well as the state of the storage system. It is to be noted that when batteries are used as storage devices, their lifetime are sharply affected by their Depth of Discharge, i.e. there is only a certain range within which a battery can safely charge and discharge while keeping a healthy lifetime. This range is given between 30% to 90% of the instantaneous state of charge (SOC) of a Lithium-ion battery, which is used in this design (Ilan Momber, 2010). A flow chart of the management system is based on the SOC of the battery and P_{net} which is shown in Fig. 4. For the first mode, when the sum of power generated by renewable technologies is greater than the load and the SOC of the battery is within permissible range, the excess power goes to the battery storage. The second mode is similar to the first where there is excess power in the network but the battery SOC is lower than threshold, hence this operating mode must be forbidden. When there is surplus energy from renewable as well as the battery SOC is higher than the upper limit, the excess power should be dumped through a load in order to avoid overcharging of batteries. On the other hand, when load demand is greater than generation by renewables, the battery storage system must provide the extra requirement, given the battery SOC is within permitted range. During discharge of battery, is the SOC falls below its lower limit, the storage system must be disconnected from load. Similarly if demand is greater than generation but SOC of battery is higher than 90%, the system enters a forbidden operating mode again. The entire process can be controlled through a set of switches, logic gates and control signals.

V. CONCLUSION

Calculations show that the large available area of the commercial vessel allows it to have substantial PV installations and thereby meet a high percentage of energy generation through PV. Although wind turbines require further investigation based on backward drag force, initial calculations are based on existing HAWT turbines which provides significant amount of renewable energy. The additional weight of the installations is also within reasonable limits to encourage potential investments in this less ventured for area. With multiple energy sources such as diesel engine, fuel cells, solar and wind turbines integrated into providing shipboard power, the presence of ESS allows attainment of efficiency and redundancy by collective usage and management of the sources. The reduction of one auxiliary generator in the chemical tanker studied in this paper allows the remaining generators to operate near their maximum power, allowing better Specific Fuel Consumption (SFC), and increased efficiency, which can result in significant fuel and cost saving, along with the mass of fuel to be carried on-board.

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