International Journal of Scientific & Engineering Research Volume 11, Issue 8, August-2020
ISSN 2229-5518



# Present and Future of All-Electric Ships in Navy Ships Based on Renewable Energy

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*Abstract*—Ten years ago the Naval shipbuilders went toward "ALL – Electric Ships" AESs technique. That enabling all ship's electric loads to supply from the same power source. Old techniques in electric ships separated the propulsion power system from the ship's service loads. Naval ships consider as an island micro-grid power system powered from the generation system and required high-density power for several types of loads. The high electric power demand, increasing the fossil fuel cost and the constraints from the international marine organizations to reduce the ship's emissions lead to looking for another clean and sustainable sources for the ship power to meet the growth in power demands.

This paper introduces the varies types of renewable and clean energy that can be used in the Naval ships and suggest the optimal solution to reduce the ship emission and take an overview of the effort from the global Naval forces to enhancement the renewable energy sources in their battleships especially using the clear Fuel cell.

*Keywords*—All-electric ships, Fuel cell, IMO, Micro-grid, Naval ship power system,

## I. INTRODUCTION

The first ship propulsion system was the sails, with the development of mechanical engineering the steam engines replaced the sails in the 19th century passing through steam turbine with high speed then The United Kingdom was developing an excellent mechanical system with reduction gears, to improve the propulsion system .at this time the United States went toward electric-drive systems. In 1908 the first commercial vessel Joseph Medill (a fireboat) was built with a turbo-electric (dc) propulsion (400 shaft horsepower).

In 1912 USA developed the collier $USS\ Jupiter^2$ as the first electric propulsion system for Naval ships. The collier was a successful research ship, with both 3,500 horsepower (hp) General Electric turbo-electric propulsion system and direct coupled steam turbine propulsion (twin-screws).

In 1914 the US Navy began to design New Mexico class battleships driven turbo-electric system, supplied from two AC generator 11.5MW, 3,000V/4,242V dual voltage, variable frequency that supplied four 3phases induction motors 7,500hp 24-/36-pole the speed control of the motor by changing the frequency (speed), voltage of the generator and reconfigure the motor connection to change the number of poles. for the ship service loads and lighting (non-propulsion electrical machinery). six 300kW auxiliary turbo-generators used. The configuration of *New Mexico class battleships* shown in Fig.1.



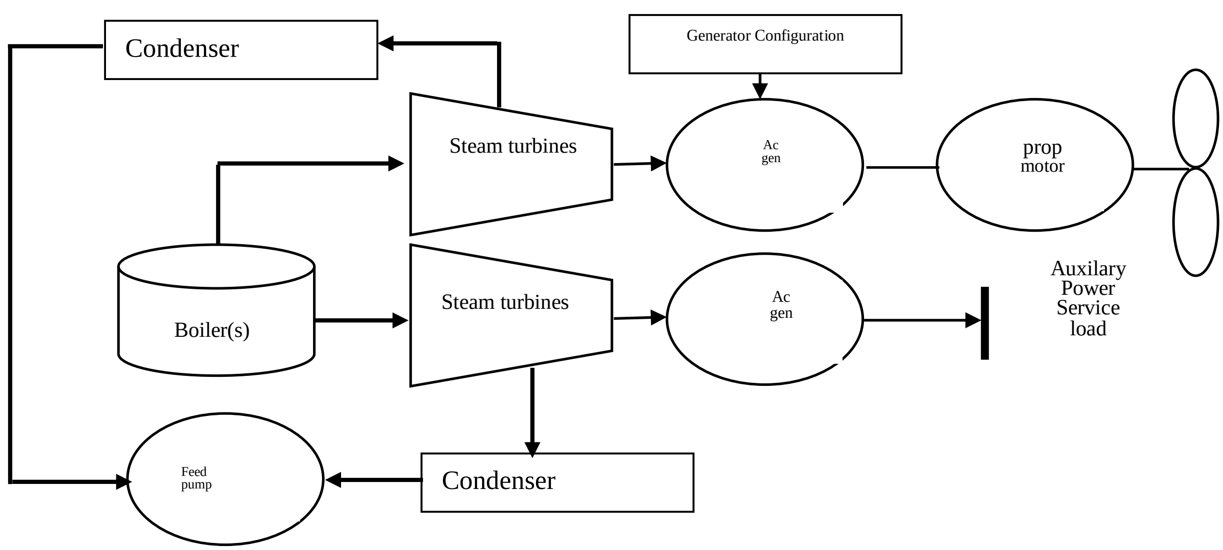


Fig.1 *Mexico class battleships* configuration.

The fuel economy for long cursing was improved, and the fast reversing of the ship heading was more easy because there wasn't need for rerouting steam turbine however the weight of the motor is more than the reduction gear but it's less in maintenance and more reliance. That old electric ships was without power electronics , nowadays the revolution in power electronics and electro mechanics make it easier and the energy management implies the All-Electric Ships technics that allow all loads supplies from the same generating system.[1]

during the time of increasing tension that went before the world war I many researches carried out to improve the battleships performance, the turbo-electric propulsion was conceived and developed. During the outbreak of WWII efforts occurred in the field of air independent propulsion (AIP) for submarines and that leads to the first submarine with AIP in end of the war. new era for Naval ships between the period 1956-1985 when the revolution of power electronic had invented and make it easy to control the electric ship machines and equipment. Nowadays the Worldwide concern about air quality, reduce pollutions and greenhouse gas emissions has led to stricter regulations in using fossil fuel and replaced with clean and renewable energy sources.[2]

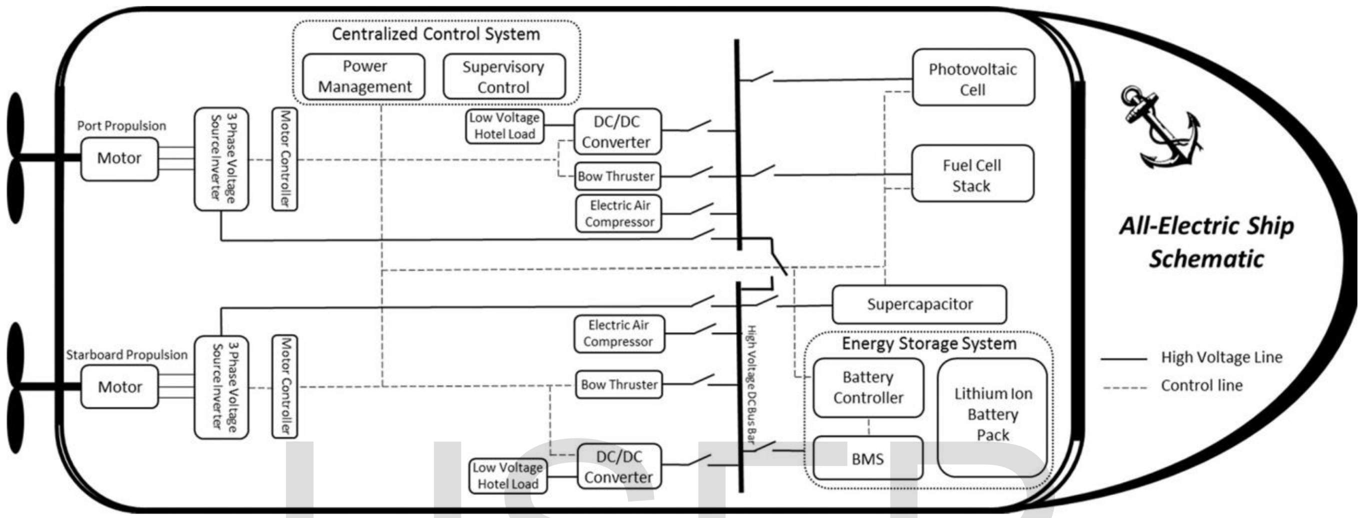


Fig 2 the schematic diagram of All-Electric ship [4]



## II. NAVAL SHIPS ARCHITECTURE.

The primary occupation of the electric power system in Naval ships will be for survivability, continuity and reliability of the electrical power supply to perform its mission. To ensure continuity of the missions, many observations shall be put into consideration, size and location of generators (power sources), panel board, and the type of electrical distribution systems to be installed and the suitability for segregating or isolating vital loads to the system .the warships need to perform its mission and safe the ship equipment's, weapon and the survivability of the fighters but in merchant ships increasing the payload and minimizing the running cost is the mail target.[3]

The ship electric power system is seen as an isolated or Island micro-grid system as shown in Fig.2. It consists of the following subsystems:

- Shipboard power generation and control system.
- Power Distribution system.
- Power Conversion.
- Energy Storage devices.
- Power Quality and Pulse Power system.
- Integrated electric power systems.

### *A. Ship power generation and control system.*

In the last century the generation and control system in ship power system is to generate the electric power and to control the output voltage by voltage control.

The main objective of generation system is to feed all the ship service equipment with the electric power to work properly, feed the propulsion system with the power sufficient to sail, be able to supply the main and backup power to the combat system during the operation i.e. supplying the sufficient electric power to the ship during all mode of operation (sailing, shore and battle mode). The increase of using renewable energy in the marine field gives the opportunity to the Naval power system to be feeded from multi-power sources this gives more reliability to the system and decrease the sailing cost and also reduced the emission from the fossil fuel.[4]

*B. Power distribution system.*

Due to the high power demand used in Naval ships the electric power distribution system had to be adapted to meet these requirements but still based on the two main schematics: the radial distribution Fig.3 that characterized by simplicity and low costs, and the zonal system put the continuity of service
is the main target Fig.4.[5]

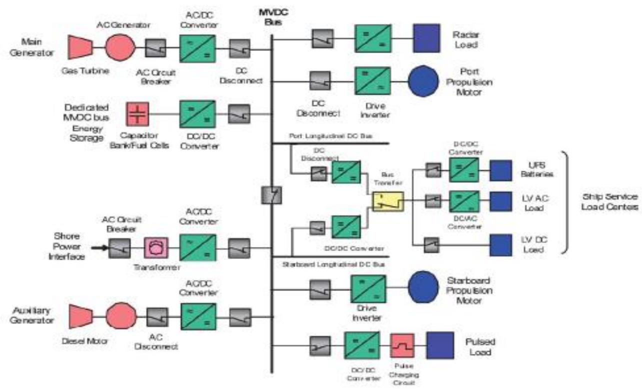


Fig 3 Radial distribution power system.[5]

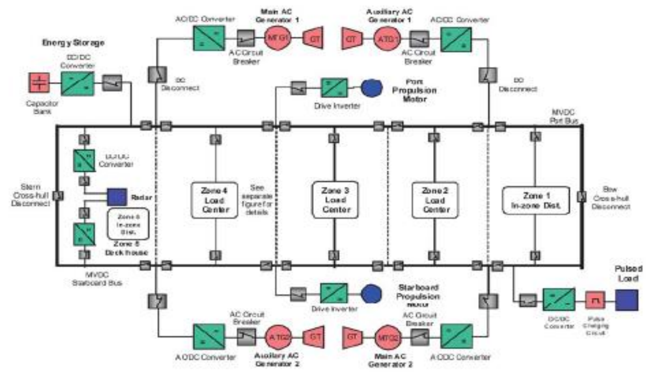


Fig 4 Zonal distribution power system.[5]

Naval Ship power system increase as the increase in the demands of the electric power. traditional three phase 440-V system is reaching the limits of breakers, cables and electromechanical switchgears. Higher voltage system is introduced to manage the high current level.

The researches of the ship distribution system were mainly to improve the dynamic performance of various source with different type of loads according to different mode of operations and to achieving maximum quality and reliability to the system in case of offering the service and higher power density.

MIL-STD-1399-300 and MIL-STD-1399-680 have established AC. voltage interface requirements for U.S. naval surface ship electrical power systems.in December 2015 MIL-STD-1399 sections had been created to use high voltage DC sources. These standard DC. interfaces are intended to facilitate the development and integration of DC. sources, loads, and energy storage system.[6].

*C. Power Conversion.*

Power conversion in Electric ships is a key for modern electric ships because varies type of sources and loads need to be converted to tie in the same bus. converting AC to DC or DC to AC or AC to AC with same or different frequencies or magnitude become an easy issue because the revolution of power electronic techniques and devices but still have the main drawbacks of heating, sizing proportional to power rating and the great impact to the ship electric power quality.

The SI semiconductor devices also reaches to its limits for higher voltage and switching frequency needed to be used in the modern battleships. The new normal rating of the ship power system the 4160-V ac or 6000-V dc with converter switching frequencies of 100 kHz. During the next five years in 2025-2030 timeframe if the naval shipboard systems power exceed100MW the System voltages will be high as 13.8-kV ac or 20-kV dc.

wide-bandgap (WBG) semiconductor devices is the new revolution in the next-generation power electronics converters due to the following characteristics compared with the SI devices low specific on-resistance, high breakdown electric field, high junction temperature capability and fast switching speed. Fast commercial development devices with WBG using silicon–carbide (SiC) and gallium–nitride (GaN) devices, with
SiC mainly to reach the high power kilowatt with high voltage 600 volt or above. another important feature of WBG beside decreasing current, it's necessary to decrease the size and weight of electronic devices Fig.4 show comparison between Si IGBT and WBG MOSFET .[7]


Fig 4 Size comparison between Si IGBT and WBG MOSFET.[7]


Fig.6 Solid State Transformer compared with traditional transformer.[7]

Traditional step up /down transformer leads to more weights and decrease the payload of the ship and also increase the radar cross section area to the battleships due to the iron and cupper that used in the transformers. Transformers rating about 20MW used as redundant propulsion system can weigh as much 35 tons. and the mutual magnetic field produced make the ship easy target for the naval mines.

Solid state transformer is introduced as a good solution to the weight and size winding transformer by increasing operating and switching frequency to high-frequency of range several kilohertz to tens of kilohertz then this high-frequency voltage is stepped up/down by a high frequency transformer with significantly decreased volume and weight, and finally, shaped back into the desired 50/60-Hz voltage to feed the load.[8]



### D. HIGH POWER ENERGY STORAGE TECHNOLOGIES.

Due to the high power density demand in battleships and through the different service mode (cruising, shore, combat.) the electric power should not be outage even in the transient time because navigation and combat system working continuously.so high power energy storage system should be connected to the power system to recover the transient switching between the main power sources and to improving efficiency and power quality of the system. In modern ships that use the renewable energy resources used to meet the energy demand integrating from renewable energy sources and improving efficiency and operating capabilities of non-renewable sources. In other words, it used to enhancement the electric power system.

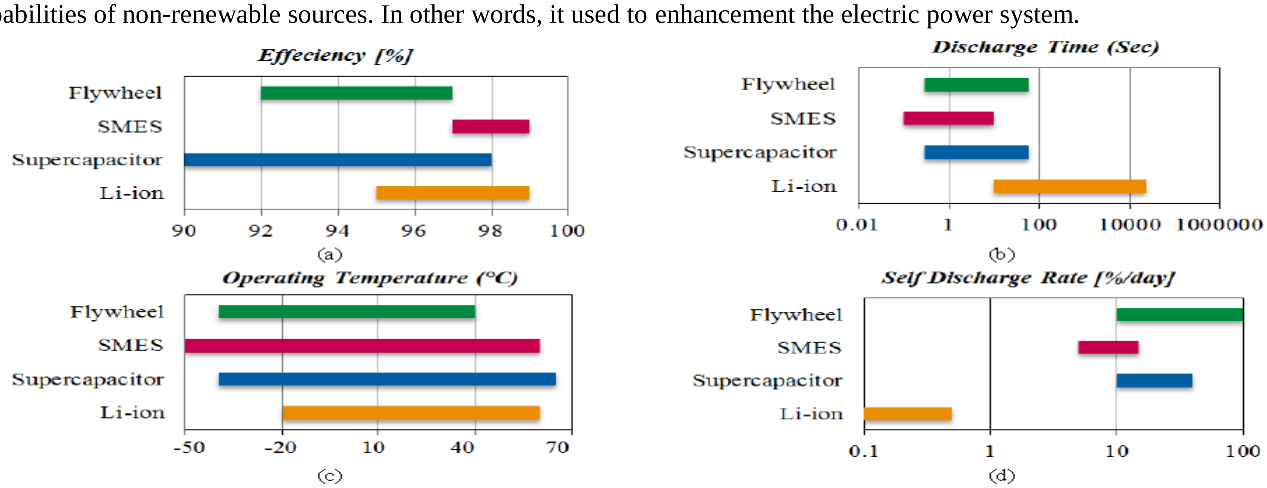


Fig. 7. Performance comparison of the high power storage technologies; (a): Efficiency, (b): Discharge time, (c): Operating temperature, (d): Self-discharge rate. [10]

Using high power and MVDC leads to advanced storage devices that using in Naval ships because it stores more power and fast and easy and less in weight and size.

- Super capacitor Energy Storage device SC.[9]
- Superconducting Magnetic Energy Storag.SMES
- *Flywheels*
- *Lithium-ion Battery*

The comparison between the four devices indicate which application it will be used for but in general all these devices working in low and high temperature and their efficiency between 90-99% with fast charging times and the fast in self charging is the LI-ion battery.[10]

Another factor in choosing the energy storing system the system life time of the device and number of cycles (charge and discharge) Fig.8 shows the expected life time for each device.

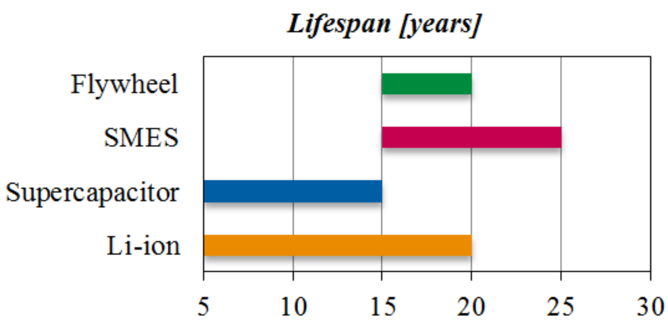


Fig. 8 Lifetime comparison of the high power storage evices.[10]

## III. Propulsion Motor system.

Propulsion motor is the core of All electric ships techniques because it's the pri-mover for the propulsion system the advantage of using electric motors are such as higher efficiency, silent operation, easy to control, low life-cycle cost and more reliable. Different classes of motors using in propulsion system from beginning the traditional DC motors and Induction motors and now as a power electronic field grows the advantage of some motor could be combined with the others and get new classes of motors suitable for evert class of ships.



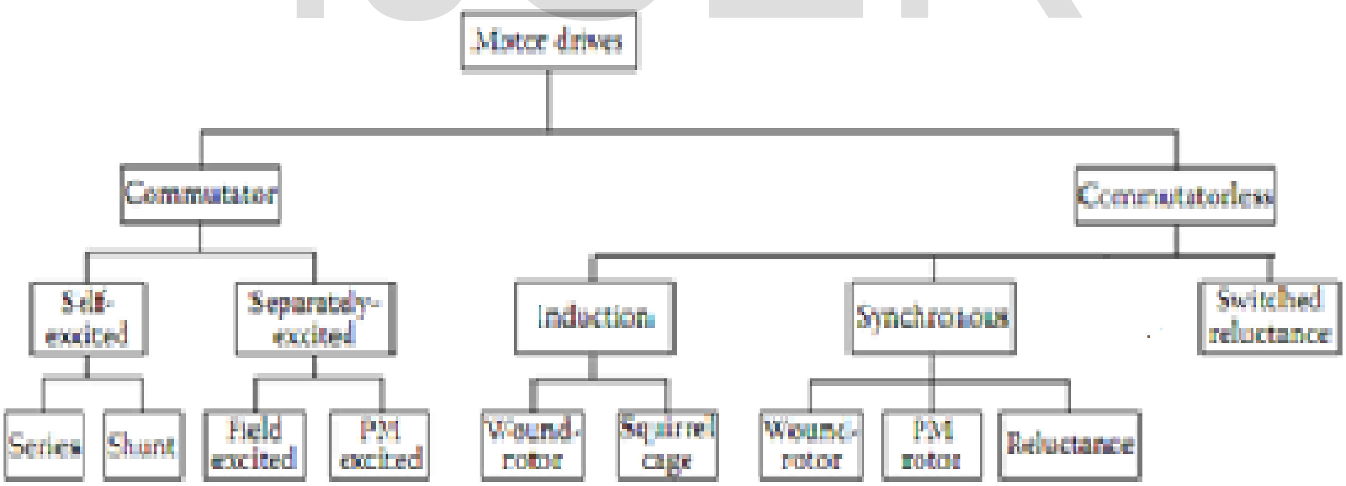


Fig. 9 Classification of motors used in propulsion systems.[11]

Motors used in ship propulsion systems can be classified into two main groups, commutation motors and non-commutation motors, as shown in Fig.9 Commutation motors are basically traditional DC motors, including excitations series, shunt excitation, excitation compound, separate excitation and excitation permanent magnet motors. DC motors inject the DC current to the armature through brushes, brushes and commutator need special maintenance and this leads to decrease the reliability of the DC motors. Recent technological developments have pushed electric motors without switching into a new era. Induction motors are widely used as a successful propulsion motor because it's easy in construction low maintenance but it had some problem in controlling speed with conventional control.[11]

International Journal of Scientific & Engineering Research Volume 11, Issue 8, August-2020
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Fig.10 induction motor used in ship propulsion system[12]

Fig. 9 solar cell in commercial ships.

With the advent of power electronics and microchip age, principle as field oriented control or vector control of induction motor have been accepted to overcome the complexity of control because of their nonlinearity.

The permanent magnet synchronous motors are also known as brushless motors with permanent magnet or permanent magnet brushless motors powered sinusoidal due to sinusoidal AC and brushless configuration (BLDC). Variable reluctance synchronous motors (SRM) and synchronous reluctance motor which have the best efficiency were recognized to have great potential for applications in electric propulsion systems. [12]

## IV. Renewable energy in naval shipboard.

The IMO put more regulation on marine field to reduce the emissions from ships to air pollutants such as SOx, NOx , COx and indirectly particulate matter (PM). Renewable energy resources found as the best solution to solve this problem. All Electric Ships technique another solution for this problem. However, these techniques would bring some challenges in terms of development ship building costs or increased technical complexity. Renewable energy is not a complete solution for several reasons because limiting of power produced from the renewable energy resources due many factors like specified area on shipboard.



### *A. solar energy in Naval ships.*

Solar energy is the most important renewable energy resources over the world because the solar power can be reached any location and the electric power produced is to produce from the photovoltaic panel and also it’s cheap power and maintenance free. Photovoltaic (PV) panels are the milestone component for converting the solar radiation to electrical energy. Solar radiation is the main factor in producing the electric power but some factors should be considered as cell temperature, environmental factors affect the transient power produced like photovoltaic (PV) located specially when the ship sailing, other factors like humidity, wind velocity, shadow and marine environment is very rigorous. It contains rich salt, hydrosphere and the acid-base material which mixed together through sea breeze.[13] Photovoltaic panel can be covered by glass will be polluted, colored, corrosive, abraded after short time and the spectral transmittance of the cover glass decreases with the increase of the submerging time in seawater. [14]

Finite area available in the Naval ships is another problem in using the solar energy but in commercial ships they find good solution to this problem as seen in Fig.11

### *B. Fuel cell*

There are many renewable energy resources can be used in naval ship but in fact not effective to have the required power. Fuel Cell technology is a promising replace the traditional combustion engine to reduce the carbon emissions on shipboard.
Fuel Cells still not used in wide range in the naval ships because it’s in low power compared with the power produced from diesel engine till 2010 the fuel cell power range not exceed several hundreds of kilowatts, but now at 2020 some fuel cells power is about 2MW.table.1 shows the range power installed fuel cell’s in marine ships during 2000-2010[15]

Table 1. Marine Fuel Cells Installation Cases.[15]

| Year | Country | Fuel Cell | Power (kW) | Name |
|---|---|---|---|---|
| 2000 | Germany | AFC | 7 | *Hydra* |
| 2002 | Japan | DMFC | 30 | *Malt's mermaid III* |
| 2002 | Germany | PEMFC | 160 | *Deep C* |
| 2002 | Switzerland | PEMFC | 300 | *Brunnec III* |
| 2005 | Germany | PEMFC | 240 | *SiNavy* |
| 2008 | Germany | PEMFC | 100 | *FCS Alsterwasser* |
| 2009 | Iceland/Canada | PEMFC | 10 | *Elding* |
| 2009 | Netherlands | PEMFC | 70 | *Nemo H2* |
| 2009 | Singapore/USA | PEMFC | 300 | *Horizon Fuel Cell* |
| 2009 | Norway | MCFC | 320 | *Viking Lady* |
| 2009 | Denmark | DMFC | 500 | *IRD* |
| 2010 | Finland | SOFC | 20 | *Undine* |

## V. Development solar cell to use in military applications.

The PV which is used in Naval ships works in a very rigorous environment. This environment contains rich salt, acid-base material, and hydrosphere which mixed the through sea breeze. So a cover glasses for the solar cell panel have been present to cover and protect the PV cells.

This cover will be corrosive, polluted, colored, abraded and so on instead of the photovoltaic modules. But the spectral transmittance for the protected shield glass reduced with a long time in the sea that leads to decrease output power obtained from the PV modules and so it will be less efficient.[14]

Two main disadvantage of using PV modules in Naval warships that increases the thermal signature of the warship because of the temperature rise due to converting the solar energy into electric energy the temperature is the main factor of the output power of the panel equation (1) and the other impact that is not sure increasing the Radar Cross Section area of the warship because of the existing of the PV modules in the ship surface.

The US Navy research center began to develop the PV technology to fill the gap between the civilian and the military application.

Naval applications have special requirements that not exist in commercial photovoltaic utilities; Naval equipment needs to withstand many pervasions. The pervasion, being stored, shipping, applied, stocked again, and shipping to the next mission. This is a specific feature for the army and Navy photovoltaic and deserves more money for research and development.

The important efforts by the naval forces in the field of solar energy is the Lightweight flexible PV that allow the curved shape of the naval ships to fully cover with the PV modules the developed modules able to deliver more power, conversion, higher efficiency, to have high specific power per kilogram (W/kg), and radiation hardness.

Special PV module invention for a specific application such that underwater PV applications. It is obvious that light energy can't penetrate the surface of the water even to a specific distance and if they success to managed and offers a sufficient power source. This PV module solves the power source for Unmanned Under Water Vehicles that was Remotely Operating Vehicles (ROV)[16]

## VI. Development of fuel cells technology in Naval.

USA started a to evaluate the advantage and disadvantage of using fuel in marine ships in the 80's, the US Office of Naval Research (ONR) has started a service fuel cell (SSFC) researches in 1997 for three stages in 2000 to design and prove that the fuel cell can be used for ships using classical hydrocarbons fuels. In the first stage designing a 2.5MW SSFC power plants was occurred. Continued research for improving the performance of SOFC.till now reaching to a 5MW shipboard SOFC system design and testing.[17]

Fuel cells is fully effective in submarines because its infiltration operation, less noise and neglected magnetic signatures, long duration in underwater operations. classical submarines are equipped with a diesel-electric propulsion system. The generated power is charging the batteries for submersed used. For fuel cells, the power capacity of the battery limits strongly the range of submersed used. This is why fuel cells are good choice to ensure the characteristic associated to the energy source of AIP. They are characterized by high efficiency, silent operation and modular and flexible design.

Fuel cell systems are the best solution for electric power source. It's more efficient and cleaner than the conventional fossil fuel engine. Fuel cell easy to integrated into an All Electric Ship Concept. But really still at the investigation and demonstration stages.[18]

## VII. Conclusion

Renewable energy is a good source of power but has many constrains in Naval ships because the sea environment and the confined space in ships and sometimes because camouflage to the military vehicles. So sustainable energy such as Fuel cell can be used in future in state of the combustion engine to reduce the emission to the environment and also to work in silent mode to overcome the enemy submarine or mines. In practical application fuel cell should work with battery and huge storage device such as super capacitor to perform hyper power system.

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