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PROJECT OF ELECTRIC YACHT PROPULSION WITH HYBRID POWER SYSTEM

DIPLOMA THESIS

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ABSTRACT

Global warming is an aspect that is increasingly concerning today's society and by which various projects and studies are being developed.The naval sector is not going to be less; it is more and more frequent to see boats with some elements that produces energy in a sustainable manner. The aim of this project is to redesign a power system of a 20 meters length yacht in order to minimize the diesel oil consumption. The yacht proposed for this analysis is the *Nomad 65* made by the company *Gulft Craft*. Subsequent to this, the use of solar panels and wind turbine has been studied. In all the project it has been taken to account the yacht have to be enjoyable and elaborated with luxurious details. In this research, it has been proofed than nowadays is still not possible to have a yacht of this peculiarities that only works with renewable energies. Solar panels and wind turbine generate too little power to operate the yacht. Moreover, there is a limited space to instal this elements without modifying outdoor areas. In order to make the yacht serviceable it has been decided to allow the charge of batteries through a plug in harbor and to instal a diesel generator on board. The technology is still not enough to minimize considerable the amount of diesel oil consumption in a yacht.

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LIST OF ABBREVIATIONS

AC: Alternating Current

BMS: Battery Management System

CCNR: Central Commission for the Navigation of the Rhine

DNV GL: Det Norske Veritas and Germanischer Lloyd

ECA: Emission Control Areas

EEDI: Energy Efficiency Design Index

EMSA: European Maritime Safety Agency

EU: European Union

EPA: Environmental Protection Agency

GHG: GreenHouse Gas emissions

ICS: International Chamber of Shipping

IEA: International Energy Agency

IFAW: International Fund for Animal Welfare

IMO: International Maritime Organisation

IPCC: Intergovernmental Panel on Climate Change

MARPOL: Maritime Pollution

NASA: National Aeronautics and Space Administration

ODS: Ozone Depleting Substances

PM: Particulate Matter

SEEMP: Ship Energy Efficiency Management Plan

VOC: Volatine Organic Compounds

WHO: World Health Organization

Chemical elements

CO : Carbon monoxide

CO_2 : Carbon dioxide

H+ : Hydrogen ion

H_2 : Hydrogen gas

H_2O : Water

HC : Hydrocarbons

NOx : Nitrogen oxide

SOx : Sulphur oxide

1. INTRODUCTION

Nowadays, we can see an increasing level of awareness from the citizens towards climate change and it's negative impact, both on the environment and human health. In fact, energy accounts for over 60% of emissions and according to the *Intergovernmental Panel on Climate Change* (IPCC) it is urgent to triple or even quadruple the share of renewables energies by 2050 to avoid catastrophic climate. In addition, there is the problem with the exponential growth of energy consumption and depletion of fossil resources that increase general concern.

That climate change issue, pollution and other environmental problems have driven the industry and Governments to create new alternatives much more environmentally friendly that could replace the current in all fields.

In the maritime world, electric energy has a widely proven advantages: not only from the point of view of energy efficiency which allows freedom of location of generating sources of energy, improvement of comfort by the absence of noise and vibration and significant reduction of maintenance.

The main objetive of this diploma thesis is to turn a luxurious yacht into an electric yacht propulsion with hybrid power system. The chosen yacht is the Nomad 65 included to the fleet of long-range yachts by Gulf Craft. It is a powerful and elegant yacht that use diesel fuel to navigate. It seeks to replace the propulsion diesel engine by an electric motor that meets the same requirements demanded of him to diesel, i.e. autonomy and power. Also noteworthy is that comfort and luxury elements cannot decrease. To carry on this project, hull forms and the interior design will not be amended.

To compensate the energy produced by the fuel, different methods respectful with the environment will be used. Thus, the implementation of solar panels, wind turbines, fuel or hydrogen batteries and lithium-ion batteries will be studied. According to the energy necessary for the correct operation of the yacht, it will be decided which of the preceding methods is more efficient. It must be taken into consideration that a hybrid propulsion system consist on many parts which must work well together. In fact, finding the right configuration and dimensioning of diesel generators, batteries, battery chargers and shore connection is essential for an efficient operation.

There are three ways to take advantage of the electric energy generated: directly, consuming the energy recovered in every moment; indirectly, by storing the energy produced in a series of batteries; and mixed, a combination of both. The most common way is the last one mentioned and is the one that is going to be used on this dissertation.

It is important to know the economic feasibility of the yacht studied since it is not a necessary object, it is only recreational and there is a lot of competition, therefore the final price is a key factor. It is known that hybrid technology requiere a higher investment cost, caused by the necessary equipment. A recent study conducted by *Bellona institute* and *Siemens* shows that, under the right circumstances, in 5-10 years the investment is returned. This is due to the reduced fuel and maintenance cost.

2. ENVIRONMENTAL IMPACT OF YACHTS

A report published at the magazine "Environmental Science & Technology" and carried out by Dr James J Corbett and Dr. James Winebrake, estimates that 60 000 deaths each year, mainly cancers and heart attacks, are caused by shipping pollution. In fact, according to the last serious research into the effect globally of this aspect of shipping, done in 2009 by the World Health Organization, one giant container ship can emit almost the same amount of cancer and asthma-causing chemicals as 50 million cars. That means that 15 giant container ship contaminate the same as all the cars in the world, about 760 million cars.

On the following diagram (Figure 2.1) it can be compared the amount of Carbon dioxide (CO_2), nitrogen oxides (NOx) and sulphur oxide (SOx) that emit the three major methods of transport.

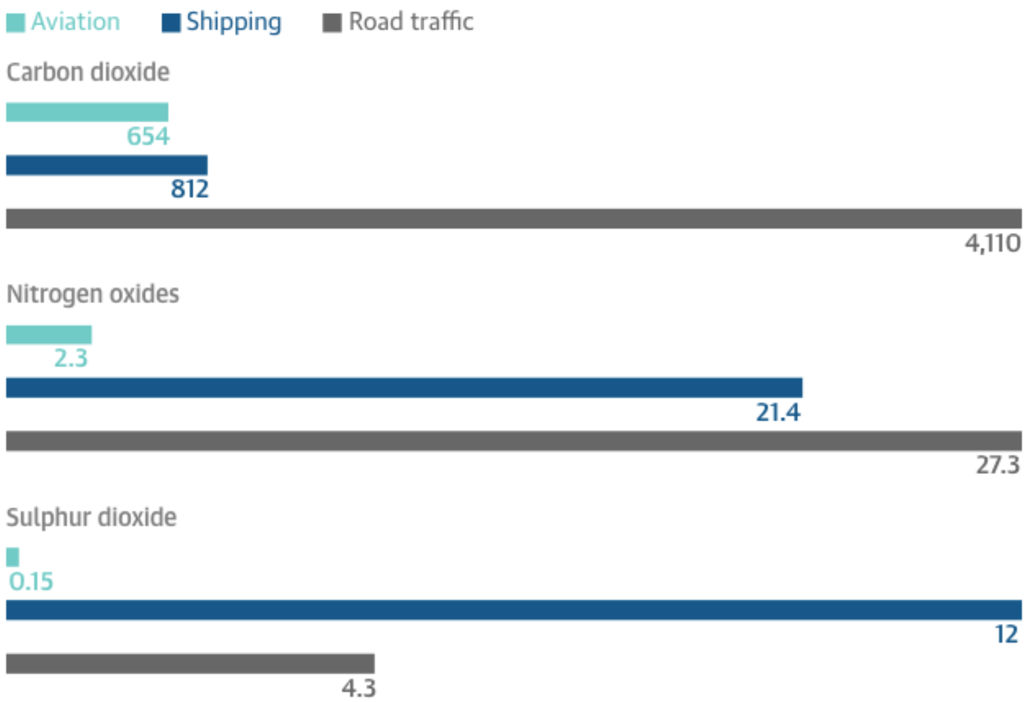


Figure 2.1: Annual emissions in million tonnes (differing scales). Source: Institute of Atmospheric Physics (DLR) (March 2007) Comparing fuel consumption, CO_2 and other emissions from international shipping and craft.

Looking at the Figure 2.1 it can be seen that shipping industry is not the most contaminant, in fact road traffic emits more carbon dioxide and Nitrogen oxides annually. In 2015, 90% of the global transport was carried out by shipping transport and issued 2.2% of the global CO_2 emissions, according to the International Chamber of Shipping (ICS). It can be thought that shipping do not emit that much emissions, instead the Figure 2.2 compares how many CO_2 emissions a motor yacht of 110m long cruising at 17 knots emits per person/mile with other types of transports. The comparison is flagrant: a motor yacht emits five times more CO_2 than large car and 250 times more than coach.

On the other hand, shipping produces three times more sulphur dioxide than road traffic. To get a better idea, let put a numerical example with reference to "The Guardian": cars driving 15,000km a year emit approximately 101 grammes of sulphur oxide gases in that time. The world's largest ships' diesel engines which typically operate for about 280 days a year generate roughly 5,200 tonnes of SOx.

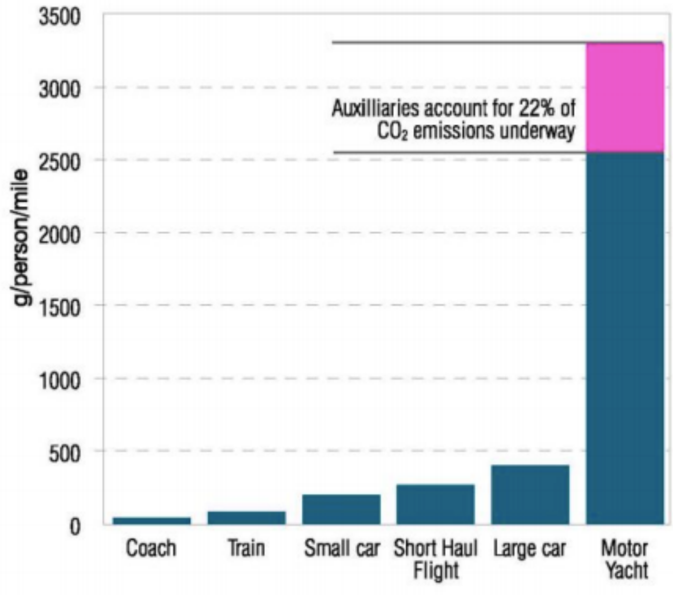


Figure 2.2: Emission's per person mile. Source: RINA Superyacht Conference 2011, BMT Nigel Gee

Worldwide organizations are concerned about the climate change and have imposed some regulations. For example, certain types of vessel built after 2016 have to be fitted with bulky equipment that converts nitrogen oxides into nitrogen and water. After this new regulations there are two different positions: some people of the industry protested that the proposed rules threatened their industry because the engine rooms of some superyachts were too small to accommodate the new equipment, meaning they would have to lose a guest cabin to make room for the technology. On the other hand, some engine builders believe that incorporating anti-pollution systems will attract more buyers, meaning that is a new marketing opportunity into their next generation designers.

It has been demonstrate that yachts contamines a lot, but luckily there is a global faith to be more careful with the environment. In fact, shipping industries believes that some changes have to be done not only to increase economic activity but also to stimulate sustainable development.

3. CONVENTIONS AND REGULATIONS

3.1. MARPOL

The expected growth of world trade represents a challenge to achieve one of the most important objectives of today's society: stabilize global temperatures while reducing emissions. In order to get results IMO has begun to implement measures and specifics techniques to improve energy efficiency of ships. Thus was formed the MARPOL. The measures taken are aimed to have a beneficial impact at the atmospheric environment and also on human health, specifically on those people living near any port.

MARPOL is short for Marine Pollution and is one of the most important international marine environmental conventions. The main objective is to minimize pollution of the oceans and seas while preserving the marine environment. In recent years already significant changes have been carried out: it has gone from 885 million tonnes of CO_2 in 2007 (the 2,8% of total global CO_2 emissions for the year) to 796 million tonnes of CO_2 in 2012 (the 2,2% of total global CO_2 emissions for the year). Therefore, in just 5 years has been reducing emissions by 89 million tonnes of CO_2.

The MARPOL is a combination of 1973 Convention and 1978 Protocol but it wasn't until 1983 that entered to force the first Annex. Nowadays, the MARPOL consists of 6 Annexes:

- Annex I: Prevention of pollution by oil produced.
- Annex II: Prevention of pollution liquids contaminants.
- Annex III: Prevention of pollution by hazardous substance transported.
- Annex IV: Prevention of pollution by sewage.
- Annex V: Prevention of pollution by garbage and waste.
- Annex VI: Prevention of air pollution produced.

The last Annex added to the International Convention for the Prevention of Pollution from Ships was in 1997 but entered into force in May 2005 and was revised in 2008. This was the first legally binding climate change treaty to be adopted since the Kyoto Protocol. On this Annex the main atmospheric pollutants are restricted, it means that sulphur oxides (SOx), nitrous oxides (NOx) and volatile organic compounds (VOC) are regulated. On top of the above, deliberate emissions of ozone depleting substances (ODS) are prohibited.

There are some specific areas that are known as "Emission Control Areas" (ECA) that have more restrictive regulations and are provided with a higher level of protection. What defines this areas is their oceanographical and ecological condition and their sea traffic. These "special areas" can be seen on the following table (Table 3.1) and map (Figure 3.1). On the map what defines ECA's zones are in dark blue.

Annex VI: Prevention of air pollution by ships (Emission Control Areas)			
Baltic Sea (SO_x)	26 Sept 1997	19 May 2005	19 May 2006
North Sea (SO_x)	22 Jul 2005	22 Nov 2006	22 Nov 2007
North American ECA (SO_x and PM)	26 Mar 2010	1 Aug 2011	1 Aug 2012
(NO_x)	26 Mar 2010	1 Aug 2011	***
United States Caribbean Sea ECA (SO_x and PM)	26 Jul 2011	1 Jan 2013	1 Jan 2014
(NO_x)	26 Jul 2011	1 Jan 2013	***

*** A ship constructed on or after 1 January 2016 and is operating in these emission control areas shall comply with NO_x Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.

Table 3.1: Special areas under MARPOL. Source: OMI

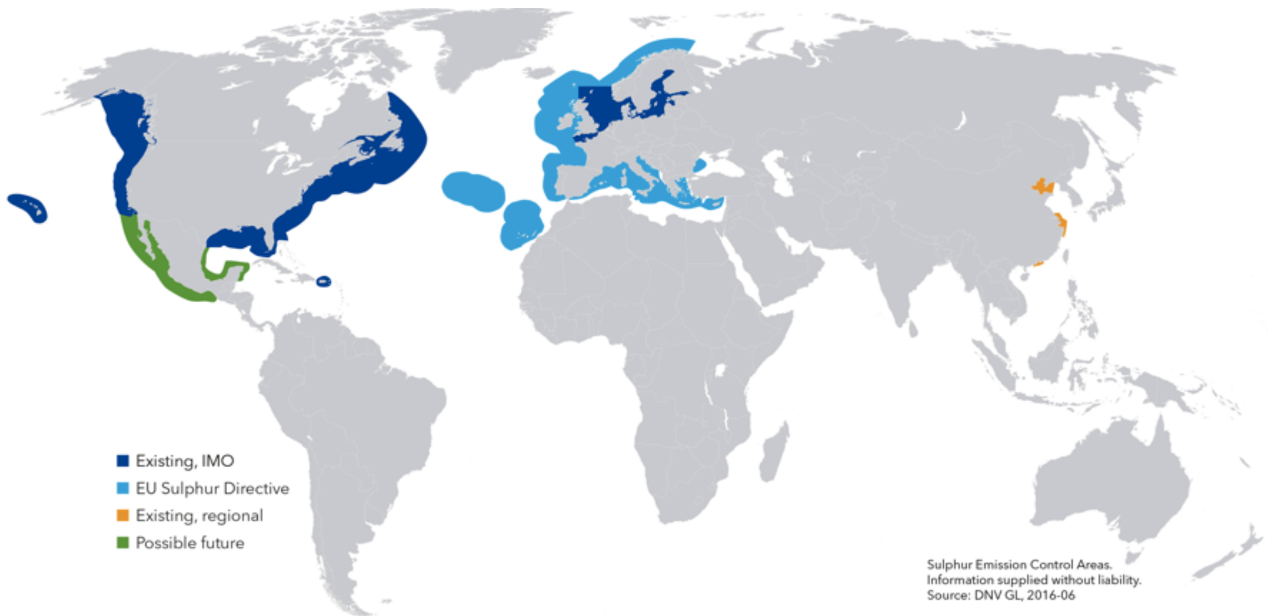


Figure 3.1: Special areas under MARPOL (June 2016). Source: DNV-GL

With regard to the amount of sulphur, MARPOL demands to decrease the percentage of global sulphur emissions from the 3,50% to the 0,50%, effective in 2020. The area defined as ECA, the Mediterranean and other areas marked in pale blue on the map (Figure 1), have special regulations referring to the amount of SOx: it has to be reduced to 0,10% from 1 January 2015.

As it can be seen, IMO has worked hard in reducing greenhouse gas emissions (GHG) while implementing mandatory measures to increase energy efficiency. Administrations have implemented the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. These measures can be found on Chapter 4 entitles "Regulations on energy efficiency for ships". The main objective is that by 2025 all new vessels will be 30% more efficient in comparison with those constructed in 2014.

The EEDI is a new technical measure for vessels whose objective is to promote the use of more efficient engines and equipment. This index is expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile. The smaller the EEDI the more energy efficient ship design. A way of defining this index in non-numerical way is as follows:

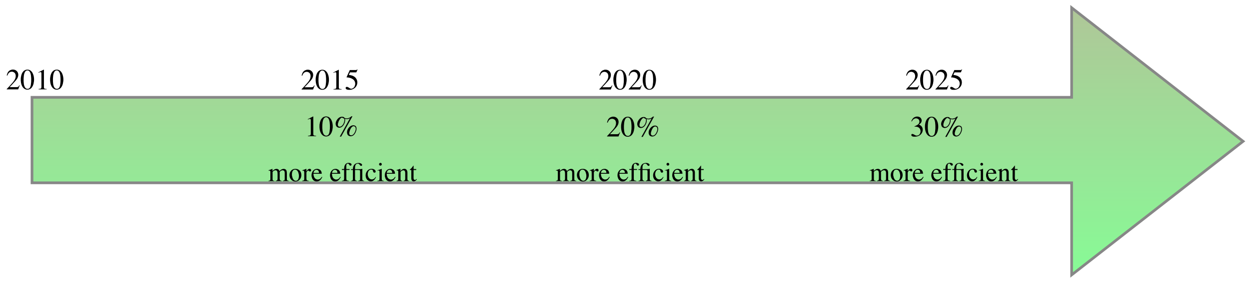
$$EEDI = \frac{\text{Impact to environment}}{\text{Benefit for society}} \qquad EEDI = \frac{CO_2 \text{ emissions}}{\text{Transport Work}}$$

The numerical formula, in its simplified way, is:

$$EEDI = \frac{P \cdot SFC \cdot C_f}{DWT \cdot V_{ref}}$$

- P, power: is 75% of the rated installed shaft power
- SFC, specific fuel consumption
- C_f is CO_2 emission rate based on fuel type
- DWT, deadweight tonnage
- V_{ref} is the vessel speed at the design load

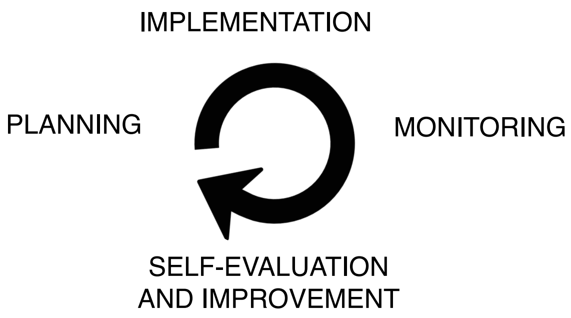
Among others, this formula takes into account the characteristics and special needs of design. Is expected that EEDI will encourage innovation and technical development of all the components that influence in a vessel fuel efficiency from its design phase. The implementation of this technic is carried out through three-step phase-in that occurs in five-year increments:



Ships delivered between 2015 and 2019 should implement 10% greater efficiency, 20% between 2020 and 2024, and 30% after 2025. On the Annex A there is the table with the applicable ship types and their respective reduction factors.
If the agreements, in accordance with this plan, are implemented is expected to reduce up to 263 million tons of CO_2 annually from 2030.

SEEMP (Ship Energy Efficiency Management Plan), in the other hand, is a tool to measure and control the emissions of greenhouse gases due to the maritime fleet. Although the greenhouse effect is a natural phenomenon, currently its value has been increased so that it promotes global warming. Since 2013 IMO have implemented this measure making it compulsory for all vessels of more than 400GT. SEEMP urges the owner and operator to consider new technologies and ways to optimize the performance of the vessel. It is a specific document of the vessel and must be linked to an energy management policy, the document will be regularly reviewed to establish the relevance and the impact of each measure in the operations of the different vessels.

It exists some specific guidelines to implement the SEEMP:



1- Planning

The owner of the vessel must develop an effective management plan to determine the current state of energy use as well as the expected improvement. This plan can be divided in four sections:

- Specific measures for the ship: such as speed optimization, maintenance of the hull or the operation of machinery.
- Specific measures of the company: its objective is the improve communication among stakeholders.
- Human resource development: is the awareness and training of the personnel who are essential to ensure a successful implementation.
- Goal setting: this aspect is voluntary and is not subject to any external inspection.

2- Implementation

This point is on the development of procedures for the management of energy, the definition of tasks and assigning appropriate personnel. Own implementation must be in accordance with the system of implementation and should include a system of record keeping.

3- Monitoring

The only way to know if this energy improvement is working is to monitor each measure. This system and the procedure for the collection of data and the personnel responsible for will be developed in the planning stage. In fact, the shipowner must carry out this monitoring through methods established by international standards.

4- Self-evaluation and improvement

It should produce a meaningful feedback to the planning of the next cycle stage. Self-evaluation and improvement not only identify the effectiveness of each measure for energy improvement, but it also determine if the process, the implementation and monitoring are suitable and how could it be improved. Each measure should be individually evaluated periodically and the results be used to understand the level of improvements noted for each vessel.

In conclusion, SEEMP provides an approach for shipping companies to improve the efficiency of the fleet and the vessel over time.

3.2. EU Regulations

The following section is based on the Regulation (EU) 2015/757 of the European Parliament, which president was M. Schulz, and of the Council, which president was Z. Kalnina-Lukasevica, of 29th April 2015 in Strasbourg. This Regulation enter into force on 1st July 2015.
Is also based on the Directive (EU) 2016/802 of the European Parliament, which president was M. Schulz, and of the council, which president is J.A. Hennis-Plasschaert of 11 May 2016. This Directive enter into forca on June 2016.

The European Union is also concerned about the climate change and have created some regulations in order to reduce the harmful effects of CO_2 and SOx emissions on man and the environment.

Concerning the first topic, all companies have to monitor and report on the relevant parameters during a reporting period each of their ships, it applies to all ships above 5 000 gross tonnage. Monitoring and reporting shall be complete and cover CO_2 emissions from the combustion of fuels, while the ships are at sea as well as at berth. To calculate the CO_2 emissions, companies have to apply a formula:

fuel consumption x emission factor

The fuel consumed by engines, both the main and auxiliary, gas turbines, boilers and inert gas generators have to be included on the duel consumption. On the other hand, the fuel consumption generated in ports will be calculated separately. In order to follow the monitoring plan, each company have to monitor the following parameters:

- port of departure and port of arrival including the date and hour of departure and arrival
- amount and emission factor for each type of fuel consumed in total
- CO_2 emitted
- distance travelled
- time spent at sea
- cargo carried
- transport work

All the Member States establish an effective exchange of information and effective cooperation between their national authorities, this way if any ship fail to comply with this regulations it can be punishable. In fact, if a ship fail two o more times the monitoring and reporting requirements, the EMSA will be notified and an order of expulsion of any port (of a member state) will be transacted.

Concerning the emissions of sulphur dioxide resulting from the combustion of certain types of liquid fuels there are some limitations. For both gas oil and heavy fuel oil ships the sulphur content can not exceed 1,00% by mass. Instead, in relation to marine fuels, Member States have to ensure that, in their territory, the sulphur content do not exceed 3,50% by mass. In addition in territorial seas, from 1st January 2020 sulphur content on those fuels can not exceed 0,50% by mass. In exclusive economics zones, pollution control zones and SOx Emission Control Areas it goes beyond: from 1st January 2020 sulphur content on those fuels can not exceed 0,10% by mass. Inside the port the sulphur content on those fuels is also restricted to a maximum of 0,10% by mass.

On the following table (Figure 3.2) there is a overview of the restrictions concerning the SOx following the EU Directives.

TYPE OF FUEL	ZONES	SULPHUR CONTENT (% by mass)
gas oil	—	1,00
heavy fuel	—	1,00
marine fuels	—	3,50
	territorial seas	0,50
	- exclusive economics zones - pollution control zones - SOx Emission Control Areas	0,10
	ports	0,10

Table 3.2: Restrictions on sulphur content according to Directive (EU) 2016/802

3.3. Central Commission for the Navigation of the Rhine

The Central Commission for the Navigation of the Rhine is an international institution that effectively treats all inland navigation issues. It cooperates closely with other international organizations, both governmental and non-governmental, who are involved in the field of inland navigation. CCNR is the oldest international organization, in fact, its history goes back to the Congress of Vienna in 1815. Nowadays it have five member state: Germany, Belgium, France, the Netherlands and Switzerland. On the other hand there are eleven observer states that follow the CCNR's rules but do not have financial contribution: Austria, Bulgaria, the Grand-Duchy of Luxembourg, Hungary, the Slovak Republic, the Czech Republic, Romania, the United Kingdom, Ukraine, Poland and the Republic of Serbia.

The main principles are: freedom of navigation and unified system of regulation for Rhine and equal treatment. On the other hand the CCNR have two key objectives: the success of navigation on the Rhine and European, and ensure a high level of security for navigation and its environment. Relevant to the first objective mentioned, their projects are:

- The guarantee of an adequate economic framework: the CCNR must promote the encounter and dialogue of different professions participating in the Rhine navigation.
- The competitiveness of the waterway: strengthen the position of the navigation compared to other modes of transport and facilitate its integration into the European transport system.

Those principles and the measures intended to apply to the entire system of inland navigation in Europe. As it can be seen on the following map there is a large route of inland navigation, the navigable zones are marked with a thick blue line.

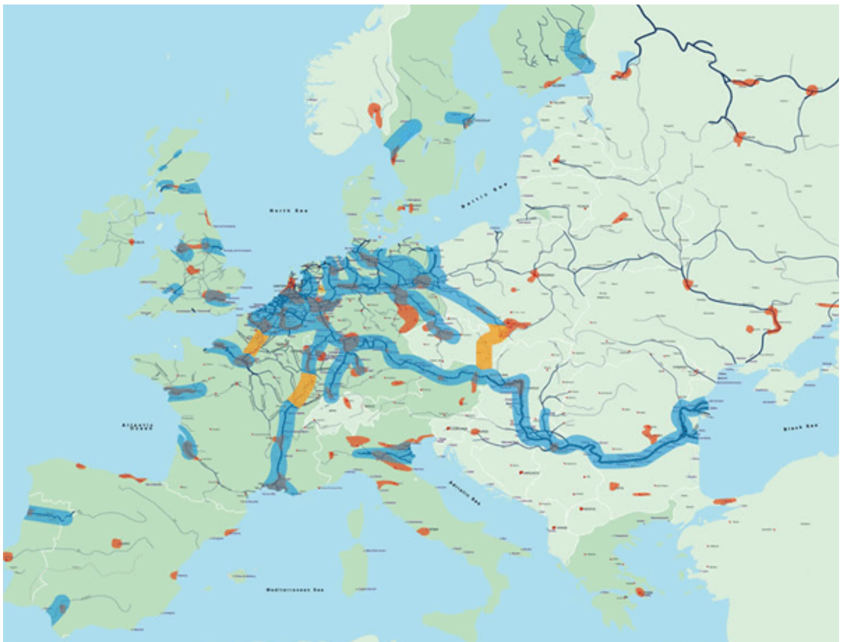


Figure 3.2: Navigable zones. Source: CCNR <http://www.ccr-zkr.org/12060200-en.html>

A very important aspect that must be put in the foreground is the efforts for the protection of the environment which in practice result in a permanent struggle against pollution in all its forms. This can be divided into two areas of action:

- accidental pollution: the protection against the pollution resulting from accidents
- operational pollution: protection at the level of the methods of work on board ships, the techniques used and the treatment of waste

Is this second area of action that applied to this thesis. The CCNR have put some measures that leads to reduce harmful exhaust fumes emissions and carbon gas emissions. Navigation worldwide is almost exclusively done with the use of diesel engines, this engines creates unhealthy and dangerous emissions for the planet. In an attempt to reduce this emissions the CCNR requires for inland vessels to install new engines that follow some restrictions. Nowadays almost everybody is concerned about climate change, that is why important thought are made by the CCNR concerning the use of alternative forms of energy such as natural gas and indeed the use of other combustion technologies, such as fuel cells.

4. ECO-FRIENDLY PROPULSION SYSTEM

4.1. Use of renewable energy

4.1.1. Introduction

In a few recent decades electric propulsion has successfully been used on ships this is due to the development of new technologies. Renewable energy use is nowadays increasing in all fields; from heading houses to substitute fuels for vehicles. Why this recent need to study and apply renewable energy? There are several advantages from using renewable energy:

- reducing energy dependence
- replacement of traditional fuels which prizes increase
- help marine environment

- Reducing energy dependence

According to the IEA (International Energy Agency), world electricity demand will have increased by 70% by 2040. Meanwhile, some 1.1 billion inhabitants (17% of the world population) do not have access to electricity. The United Nation has established an ambitious objective: by 2030 everyone should have access to electricity.

On the other hand, dependence on fossil fuel imports results in subordination to the economic and political short-term goals of the supplier country, which can compromise the security of energy supply. Oil and natural gas are the main cause of some wars on the last years. however everywhere in the world there is a renewable source (wind, sun, water or organic material) available for producing energy sustainably.
It might me concluded from this that lot of lives depend on energy sources and that renewable sources could be the solution.

- Replacement of traditional fuels which prizes increase

Traditional fuels are a scarce resource; they are liquid fossils that are stored beneath the Earth and whose reserves will not increase, the only thing that is done is spend it. Therefore, in general, the trend is that every time there is less oil reserves in the world because it is only consumed and does not grow. As everyone needs oil because both factories and cars are based on the use of it, this system is not sustainable and the use of renewable energy is needed.
On the other hand, petroleum prizes can increase for other reason as political ones. For example, nowadays, United States is making the prize increase and therefore people will consume it less. In this way, their core competencies, which their economy is based on oil exports, will be affected negatively.

- Help marine environment

The World Health Organization says that noise is one of the environmental factor that causes more diseases.

Ships with modern hybrid technology do not generate that much noise emissions. This is an important issue for animals living on the sea and people near it. In large water bodies, sound waves can propagate along kilometers without losing intensity. The presence of sounds of great power or from boats or sonars can alter patterns of migration, communication, hunting and reproduction of many marine animals, specially mammals such as the whale and dolphin. Mark Simmonds, Scientific Director of the Society for the Conservation of Whales and Dolphins, said that there is evidence that cases of whales stranded on beaches around the world are increasingly more related to noise pollution. In fact, according to a study led by the IFAW (International Fund for Animal Welfare), the maximum distance to which blue whales can communicate has been reduced by 90% as a result of the high levels of noise.

In a port there is usually lot of noise due to the work done there: not only there is the noise of ships but also of people working loading and unloading them. In Spain some measures have been already taken to reduce noise at the harbors. The port authority has established the following sound levels of reference:

- Residential urban areas: 55dB during the day and 45dB at night
- Industrial or storage areas: 70dB during the day and 65dB at night

According to the WHO (World Health Organization) the acceptable limit of noise for the human ear is 65dB. That means that people working on harbors are on the limit of acceptable noise, so they are highly exposed to the consequences of this noise. The consequences can be hearing, psychological, physiological problems and sleep disturbances.

Instead an investigation made by Joint Task Force shows that a yacht without a muffler produces a sound level of 100 dB at a distance of 15 meters and one with under water exhaust 85 dB at the same distance. That shows that measures stablished can not be followed. However hybrid yacht can comply with the regulations. For example the Grace E yacht, with 73 meter of length, produces very few noise while cruising at 14 kn: measuring 45,5 dB in the saloon and 42,6 dB in the master suite according to an article in BOAT concerning about "The quietest superyachts in the world".

In top of the above, according to the EPA (United States Environmental Protection Agency) human activities are responsible for almost all of the increase in greenhouse gases in the atmosphere over the last 150 years. On the United States nearly 28,5% of 2016 greenhouse gas emission were due to transportation, primarily from burning fossil fuel. Over 90% of the fuel used for transportation is petroleum based, which includes gasoline and diesel. Diesel engine, like other internal combustion engines, converts chemical energy contained in the fuel into mechanical power. Ideally, diesel fuel is a mixture of hydrocarbons which only produce carbon dioxide (CO_2) and water vapor (H_2O). Indeed diesel emissions include also pollutants that can have adverse health and/or environmental effects. Common pollutants include unburned hydrocarbons

(HC), carbon monoxide (CO), nitrogen oxides (NOx) or particulate matter (PM). In the figure 4.1 there is a diagram showing the distribution of pollutant emissions, before the introduction of advanced treatments in diesel engines.

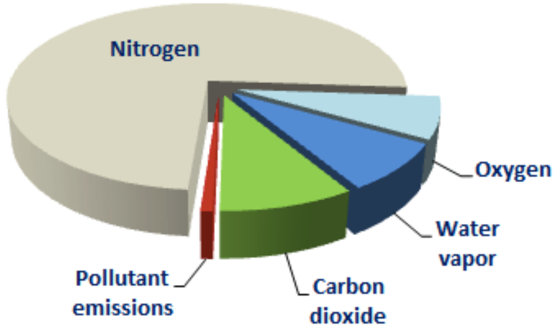


Figure 4.1: Relative concentration of pollutant emissions in diesel exhaust gas. Source: MAJEWSKI, Addy (2012) What are diesel emissions, DieselNet Technology Guide.

Most of these pollutants originate from various non-ideal processes during combustion, such as:

- incomplete combustion of fuel
- reactions between mixture components under high temperature and pressure
- combustion of engine lubricating oil and oil additives
- combustion of non-hydrocarbon components of diesel fuel, such as sulfur compounds and fuel additives

There are other sources that can contribute to pollutant emissions from internal combustion engines, usually in small concentrations, but in some cases containing material of high toxicity.

4.1.2. Wind

Wind energy is the energy obtained from the wind, that means, the kinetic energy generated by the effect of currents of air and that is transformed into useful forms for human activities. Since ancient times it has been used for different purposes such as for example move the ships powered by sails or to run the mills machinery to move their blades.

Basically sailboats receive the impulse of the wind and propel the boat through a sail that depending the angle between the wind and the surface will produce a movement in the direction where there is less pressure. In order to optimized wind energy there are different types of sails. Sails have experimented a spectacular evolution during the last decades. For hundreds of years sails were made with natural fabrics but where to little and heavy, especially when they goy wet: these fabric were such as papyrus, linen, leather and cotton. Investigations have permitted and up-grade: nowadays sails, usually made of synthetic fiber, are lighter and more resistants.

Aerodynamic theories have allowed to establish the basic principles of operation of the new aeroturbines thus optimizing already established designs.

It was in 1927 when Albert Betz showed that it was not possible to extract more than 59% of the energy contained in the wind and Hermann Glauert Singularity set theories in which is based the aerodynamic behaviour of the modern aeroturbines.

As proved by A. Betz, the maximum value of mechanical power that can be extracted is calculated in the following way, according to the rule no turbine can capture more than 16/27 (59,3%) of the potential energy wind:

$$P_{\max} = \frac{16}{27} \cdot \frac{1}{2} \rho A v^3$$

On the other hand, the British Glauert described in a very general way the behavior of the aeroturbina with three characteristic values: the coefficient of traction (CT), the coefficient of par (Cq) and coefficient of power (Cp). The last coefficient can be understood as the performance of the wind turbine, that is to say, the percentage of energy contained in the wind that will be transformed into mechanical energy.

These two physicists get to determine the fundamental principles on the issue of wind energy.

A wind turbine is a device that converts the kinetic energy of the wind into electrical energy. That is to say, it is a generator driven by a turbine driven by the wind (wind turbine). A wind turbine, in a manner very similar to that of a traditional windmill, is based on the principle of resistance offered by the blades to the wind. The study on the aerodynamic and structural design of the blades allows to increase the performance of wind turbines.

When there is air in motion the rotor blade will rotate. Depending on the wind speed the wind turbine use one technique or another: if the speed is between 2m/s and 3m/s the turbine will be facing the wind, otherwise if the wind speed is more than 3m/s the turbine will spin normally. The blades caught the energy of the wind and transfer the power to the low-speed shaft. Within this area can be found the behavior of the electrical or hydraulic system which are connected with the multiplier. Through a gear inside the multiplier the output shaft will rotate with greater frequency which allows the operation of electric generator. It is this element that converts mechanical energy into electrical energy. The electricity produced will leads to the base of the tower where it will produce some changes (lower the intensity, reduce global warming wiring) before sending it to the network. This energy can be stored in batteries and, subsequently, it can be used both to move the propeller system or for appliances, lights.

The negative aspect are that in order to move the propeller of a medium yacht it is needed a wind turbine of considerable dimensions and that the rotation of blades at full speed creates noise.

4.1.3. Solar Energy

The sun have illuminated the Earth for about 5 billion years and it is estimated that it has not arrived in the middle of its existence yet. So, compared to other source of energy it is not only clean but also inexhaustible. But how do these sun rays transform into electricity? Photovoltaic energy.

Photovoltaic is the transformation of direct solar radiation into energy. This transformations takes places on devices known as photovoltaic panels. This plates are formed by modules and these modules formed by photovoltaic cells. The cells are composed of one, or several, laminates of semiconductor material and covered with a transparent glass that allows solar radiation to pass and minimize heat loss. These photovoltaic solar cells can be made of silicon or other cheaper material but with lower performance. In fact, those built with silicon have a yield of 14% — 17% and the other, also known as second generation cells, if 10% — 12%.

How is energy obtained? Photons of solar rays strike photovoltaic cells creating an electric field between the layers. Although there is no need for direct light, the more intense it is, the bigger the electricity flow will be. Photoelectric cells transform solar energy into electricity in a continuous current but home appliances usually use an alternating current, so an investor is needed. This inverter not only transforms the continuous current into alternating but it also controls the uniformity and quality of the signal.

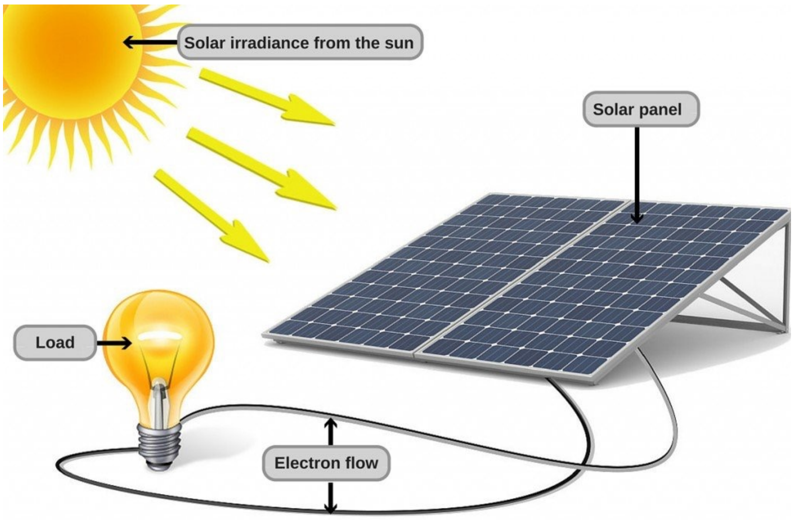


Figure 4.2: Schema of how solar radiation works. Source: <www.solarworksforamerica.org>

4.1.4. Wave energy

It is known as marine energy or sea energy that set of technologies that harness the energy of the oceans. It has an advantage that no other system can give: it is easy enough to predict the movement of the waves and

therefore the energy that will be obtained. However, the different sea conditions with high forces in waves and marine corrosion make this technology require great investments and is still not quite well developed.
The concept of marine energy is wider and it encompasses many technologies but only the ones that have direct application to the naval scope will be commented.

Waves are created by the interaction of the system composed of the Earth, the moon and the sun, therefore this is a free and inexhaustible energy source.
Although it seems difficult to imagine a boat that uses tidal energy to propel itself, it already exists: this is the case of Suntory Marmaid II. Despite being the project that is best known, it is not the first. In fact it was in 1895 when the idea of a wave-powered ship was applied for the first time. Until a century later there was little progress in the subject and it was Yutaka Teran and a colleague who made a prototype of a single-seater with the help of the company Hitachi Zosen Corporation. In this first prototype, a single fin of almost 4 meters was used for a boat of 20 tons at a speed of 2 kn. To improve the performance of the project they designed a mechanism with double fin.

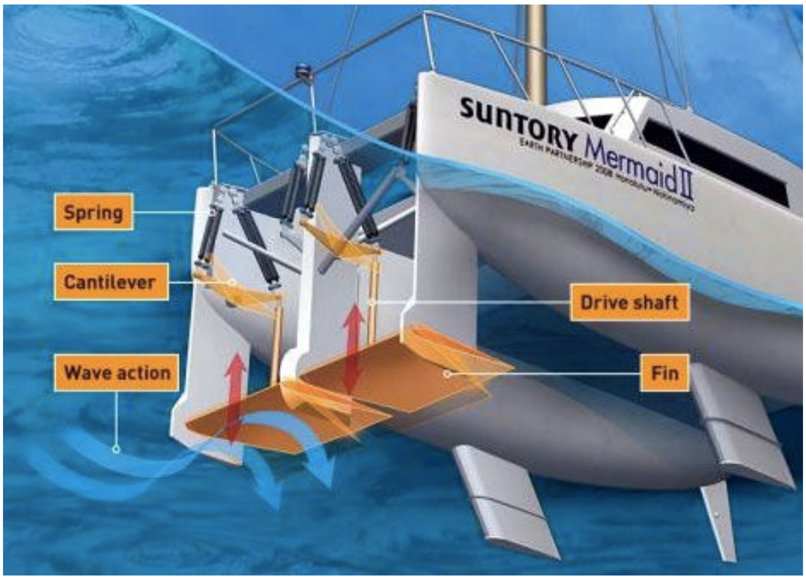


Figure 4.3: Schema of how works Suntory Marmaid II. Source: HANDS, Kevin (2008) How to ride waves, Popular Science.

Later, the Japanese Yutaka Terao designed the current catamaran that has a length of 31 feet and a weight of three tons. The boat consists of a system propelled by waves set to the bow below the waterline. This system has a basic principle: it has two horizontal and parallel fins that capture the energy of the movement of the sea. With each wave the fins are balanced similarly to the fin of a dolphin. In this way, it is possible to propel the boat at an approximate speed of 3 kn with very good stability.

The Fraunhofer institute has patented a new technology called Mobile Wave Energy Harvesting, which is based on taking advantage of the waves movement at sea. This American and European company has designed enormous buoys capable of anchoring in a ship to collect electrical energy wherever it goes. It consists of articulated arms connected to small generators that are linked to buoys of about 50 meters in diameter set on each side of the helmet, as it can be seen in the Figure 4.3. These arms open during the crossing and take advantage of the energy of the waves to generate electric current and store it in batteries. In total, it could be stored up to 20 megawatts per hour.

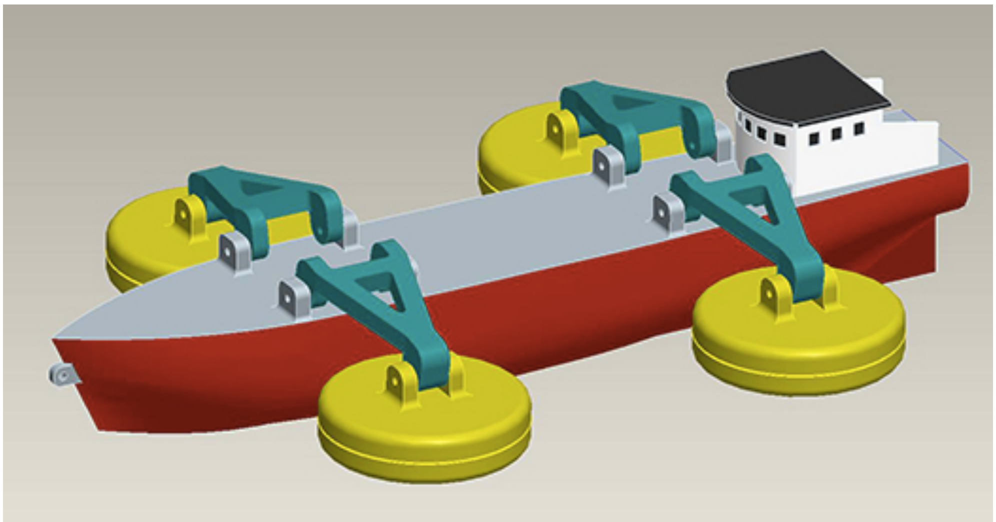


Figure 4.4: Drawing of Mobile Wave Energy Harvesting. Source: Fraunhofer CMI - Center for Manufacturing Innovation

4.1.5. Biofuel

Historically biofuel appeared at the 20th century when Henry Ford planned to fuel one of his models, the Model Ts, with ethanol, according to Kanchan Bala in the *International Journal for Innovative Research in Science & Technology*. Despite a huge petroleum deposits where found and kept gasoline and diesel cheap for decades leaving biofuels forgotten. However, nowadays biofuel have been regaining popularity due to the rise in oil prices and the concern about global warning caused by carbon dioxide emissions.

Biofuels are combustible fuels created from biomass. That means that they are fuels created from recently living plant matter, opposed to hydrocarbons (diesel, petroleum) that use ancient plant matter. There exists a large list of biofuels but the main types are ethanol and biodiesel. The way to distinguish between them is: ethanol is an alcohol and biodiesel is an oil. Ethanol is an alcohol fuel made from the sugars found in grains such as corn, sorghum, and barley. Alcohol is made by fermenting sugar; sugar crops are the easiest ingredients to convert into alcohol. It can be used as a replacement or additive to gasoline. Whereas biodiesel is a fuel made from vegetable oils (soybean and canola), fats, or greases and it is produced by extracting oils in a process called transesterifications. Biodiesel fuel has chemical characteristics similar to petroleum-based diesel, so it can be used as a direct substitute for diesel fuel. Biodiesel fuel can also be blended with petroleum diesel in any percentage without reducing vehicle fuel economy.

Figure 4.5: Ethanol process & Biodiesel process. Source: FREWIN, Chris - Biofuels, Student Energy.

Based on the type of feedstock used to produce biofuels, it exists three categories:
- First generation: produced from food corps (ethanol and biodiesel).
- Second generation: produced from cellulosic material such as wood, grasses and inedible parts of plants. This material is more difficult to break through fermentation and therefore requires pre-treatment before it can be processed.
- Third generation: produced using the lipid production from algae.

In addition, the term "Advanced Biofuels" is used to describe the relatively new technological field of biofuel production that uses waste such as garbage, animal fats, and spent cooking oil to produce liquid fuels.

There is also a negative part in all this: growing biofuels takes energy, can lead to deforestation and minimize biodiversity. Grow biofuels takes fertilizer, tractors, transportation and energy to convert the plants to liquid fuels. According to a fuel properties comparison made by the U.S Department of Energy in 2014 the energy content of Biodiesel and Ethanol are the followings:

	Biodiesel	Ethanol
Lower heating value	27,81 MJ/kg	11,75 MJ/kg
Higher heating value	29,76 MJ/kg	19,66 MJ/kg

Table 4.1: Heat value comparison between Biodiesel and ethanol. Source: Alternative Fuels Data Center — Fuel Properties Comparison (29 October 2014) U.S Department of energy.

Indeed, growing biofuels on existing agricultural land can displace food production to previously non-agricultural land such as forests. Trees absorb CO_2 from the atmosphere, for instance removing them for biofuel production may result in an increase in net greenhouse gases instead of a decrease. Not least, it is very important to ensure biodiversity: even if growing a single type of corn is easier for producing biofuels (it can be possible to select the type of corn that best suits with the yield and require least amount of water), it will make the pest that eat this type of corn to proliferate. What is worst, the pest will inevitably become resistant to the pesticide after a while.

To combat those issues, new European rules came into force in 2015: the Directive 2009/30/EC and 2009/28/EC of the European Parliament and of the Council of 23 April 2009. On them, for example, it is expressly indicated that biofuels cannot be produced from land with high value in terms of biodiversity (forests, meadows) or from land with high carbon stock. In addition, One way for companies to demonstrate that their biofuels comply with the criteria is to participate in voluntary schemes that have been recognized by the European Commission. They mainly check that biofuel production did not take place lands specified on Directive 2009/30/EC and that leads to a sufficient level of greenhouse gas emissions savings.

4.2. Hydrogen and fuel cell

According to Ed Fort, Lloyd's Register's senior project engineer:

"The operation of fuel cell generators on existing marine fuels such as marine diesel oil presents the biggest technical challenge but the largest potential market for early marine fuel cell generators"

A fuel cell is a device that generates electricity by a chemical reaction. Every fuel cell has two electrodes, the anode and the cathode, where the reactions that produce electricity take place. Every fuel cell has also an electrolyte which carries electrically charged particles from one electrode to the other. Is very important to choose the right electrolyte because it must permit only the appropriate ions to pass between the anode an the cathode, if free electrons (or other substances) travel through the electrolyte, the chemical reaction would be disrupt. There is also a catalyst which speed the reactions at the electrodes.

Fuel cells requires, generally, hydrogen and oxygen. Although there are several kinds of fuels cell which operates a bit differently (distinguished by the type of electrolyte employed, the oxidant and fuel) let explain how a fuel cell works in general terms. In the Figure 4.3 there is a scheme about the operation. Pressurized hydrogen gas (H_2) enter the fuel cell on the anode side. This gas is forced through the catalyst by the pressure [1]. When an H_2 molecule comes in contact with the catalyst, it splits into two H+ ions and two electrons (e-). The hydrogen atoms are now "ionized," and carry a positive electrical charge. The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell [2].

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge [3]. This negative charge attracts the two H+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O) [4].

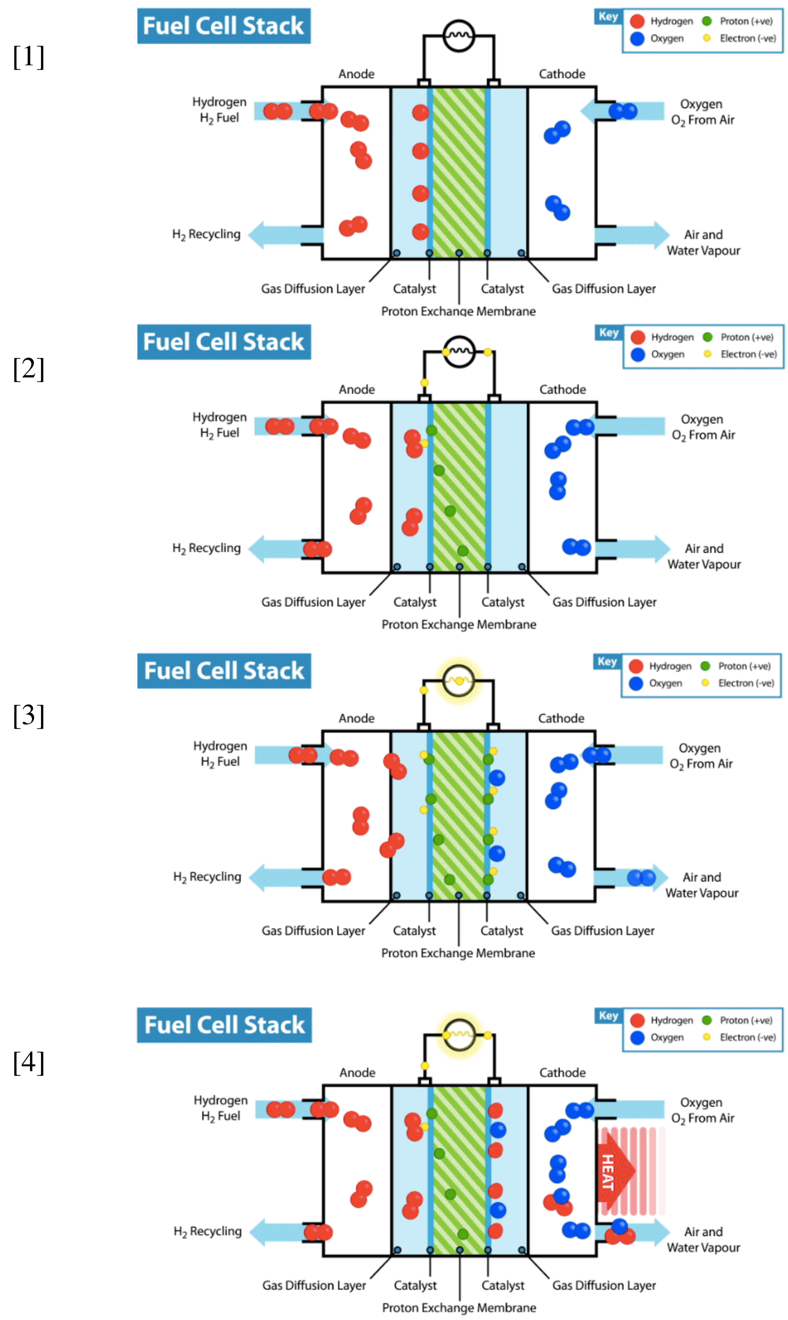


Figure 4.6: Scheme explaining how a fuel cell works. Source: Intelligent Energy Limited (2018) What is a fuel cell?

One great appeal of fuel cell is that they generate electricity with very little pollution–much of the hydrogen and oxygen used in generating electricity ultimately combine to form a harmless byproduct, namely water.

In fact, NASA explain on his official page that they had used liquid hydrogen since the 1970s to propel the space shuttle and other rockets into orbit and the fuel cells,used to shuttle electrical system, produce a clean byproduct: water, which the crew drinks.

Despite this,actually there are two problems with fuel cells. In the first place is the obtention of hydrogen. Currently most industrial hydrogen is derived from methane and the carbon is rejected as carbon dioxide, thus adding to the greenhouse effect. Secondly there is a problem with storing and transporting the hydrogen gas: it is extremely difficult to liquefy and it is very dangerous to keep it as a gas under pressure.

4.3. Lithium-ion Batteries

A Lithium-ion battery works just as in every other battery. There is a positive and negative electrode called the cathode and the anode. The cathode is made of a very pure lithium metal oxide; the most uniform is the chemical composition, the better the performance and the longer the battery life is. On the other hand, the anode is commonly made of graphite, a form of carbon with a layered structure. The battery is field with a transport medium: the electrolyte that must be extremely pure and as free of water as possible to ensure efficient charging and discharging.

In order to charge the battery, the positive charged lithium ions have to pass from the cathode through the separator into the graphite structure of the anode where they are stored. When the battery discharges is when energy is removed from the cell: the lithium ions travel via the electrolyte from the anode back to the cathode. The motor converts the electrical energy into mechanical energy. The amount of energy available and how long the batteries last is closely related to the quality of the materials used.

Lithium-ion batteries are popular because they have a number of important advantages:

- High energy density: lithium is a highly reactive element, meaning that a lot of energy can be stored in its atomic bonds.
- Hold their charge: a lithium-ion battery pack loses only about 5 percent of its charge per month, compared to a 20 percent loss per month for nickel-metal (NiMH) batteries.
- No memory effects: they do not have to completely discharge before charging.
- Hundreds of charge/discharge cycles.

Alternatively, there are a few disadvantages as well:

- Start degrading as soon as they leave the factory
- Extremely sensitive to high temperatures: degrade much faster and can burst into flame.

For all these reasons, many have been looking into how to make a battery more durable, useful and safe. Latest trends pointed to Graphene but a recent study of Standford University, carried out by Hongje Dai, just find that made Al-ion (aluminum ion) batteries are a substitute with high properties: they do not burnt and have longer life.

4.4. Hybrid propulsion system

The main objetive of this thesis is to use renewable energy in order to design a yacht that works with both electric and diesel engines. This is not a pioneer idea, as it can be seen on Chapter 5 of this thesis. Hybrid yachts have lot of advantages, not only is it environmentally-friendly but it also spends little fuel for what ends up being economically profitable. Moreover, it brings the opportunity to navigate in complete silence, without any kind of noise and smoke. The sensation is similar to sailing but without the need of handling the capes of the sails and without heeling. Afterwards it will be explained how works and hybrid yacht using solar energy and batteries: the main system components and operational modes will be highlighted.

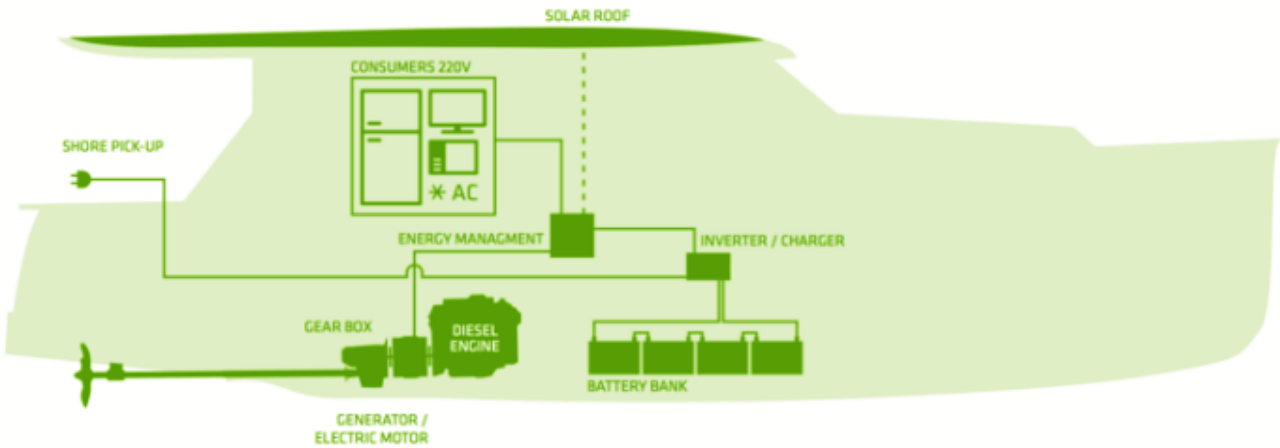


Figure 4.7: Diagram of the layout of different elements in a hybrid boat. Source: <https://www.greenlinehybrid.es>

Let explain how works hybrid yacht depending on the operational mode, but firstly it is important to know how the batteries works.

In order to charge the batteries there exists two different ways: using solar energy capture by the solar panels on the roof of the sun deck or charging the batteries through a plug on the shore. To use this stored energy, the use of a inverter will be required to supply electricity in AC (alternating current). Otherwise appliances and other sources that consume energy could not be used.

- Electric propulsion: stored energy in batteries go through the generator / electric motor and active the gear box that will spin the propeller.
- Diesel propulsion: in case that the stored energy is not enough, the diesel engine will be used. Diesel engine will drive the boat and is the generator which will take energy to the batteries so that they can provide consumers.

Diesel engines do not have a optimum fuel consumption until they reach the last stage of maximum power, as a result the hybrid systems are used to navigate with electric power in the first ranks of speed. Generally, the propeller is designed to reach the maximum rpm and for a hight speed; for lower speeds, the engines are disproportionate and spend more fuel than is really required. Consequently an hybrid system allows save fuel and increase tanks autonomy.

It is worth to know that batteries will need a large space and have to follow some specific rules. The following section is based on the DNV GL -Rules for Classification Ships, “Part 6 Additional class notations, Chapter 2 Propulsion, power generation and auxiliary systems”. This chapter will follow the rules of the edition of October 2015.

All the following rules are only applicable for vessels where the battery installation is used as an additional source of power and has an aggregate rated capacity exceeding 50kWh.

There are some regulations about the design when using batteries:

- battery spaces shall be positioned aft of collision bulkhead.
- the battery space shall not contain other systems supporting essentials vessel services (pipes and cables serving such system).
- the battery space shall not contain heat sources or high fire risk objects, in fact the space should have ventilation that can provide air with temperature control of the ambient temperature.

Regarding the Battery Management System (BMS) there are also some specific regulations. The BMS shall:

- provide limits for charging and discharging to the charger.
- protect against over-current, over-voltage and under-voltage.
- protect against over-temperature.
- control cell balancing.

Finally, it must be always available for users to know the system voltage and the temperature, the max/min and average of both parameters, through control panels or in remote workstations.

5. EXAMPLES OF SOLUTIONS

The experienced gained in past centuries shown that all new technologies are first applied in military industry. In fact, the first successful application of a parallel hybrid solution system had place in a submarine at the beginning of the 20th century. Nowadays hybrid propulsion system is being developed by multiple enterprises all over the world and is also the object of numerous researches. On the following chapter let see some examples of hybrid solution applied on recreational boats (although there are military ships and commercial ships with hybrid power they will not be commented here).

First of all is it worth to now that a homogenous totally electric boat is possible: a very famous and popular ship that uses solar energy is the catamaran *PlanetSolar*. This catamaran has done a voyage around the world, which have finished in 2012. For many years there have been some researches about photovoltaic panels, which are considered source of clean, "green" electric power and this catamaran has shown that solar energy can be a significant source of energy. On the Annex B there is a overview of all the important characteristics of the ship: the speed and the capacity of people proof that it could be used as a recreational boat but the fact that all the sun deck is covered by 512m^2 of photovoltaic cells (as it can be seen at the Figure 5.1) is a disadvantage.

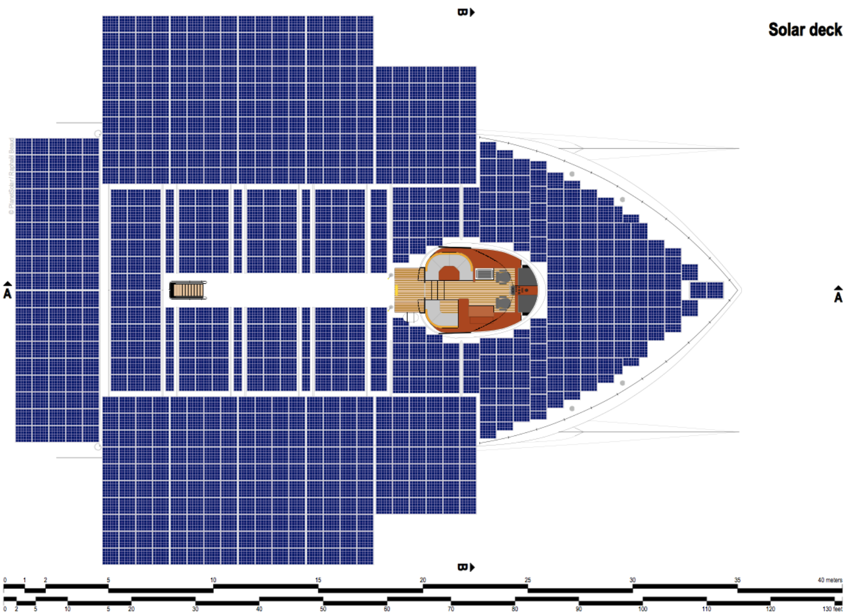


Figure 5.1: Boat layout, solar deck of the *PlanetSolar*. Source: <http://www.planetsolar.ch>

Another company that offers 100% electrical boat is *Canadian Electric Boat Company*. This company have three types of small boats that works with outboard motor and least up to 12 hours. Afterwards is an example with the characteristics of one of their models, the *Fantail 217*. Is a small yacht without any bathroom or any cabin. Therefore, this type of boat can not be assimilated with the yacht studied in this thesis.

Figure 5.2: Fantail 217, Canadian Electric Boat Company. Source: <https://www.electricboats.ca/en/>

Overall Lenght	6.60 meters / 21 ft 7 in	**Engine Type**	Minn-Kota
Overall Width	2.03 meters / 6 ft 8 in	**Engine Power**	2 HP
Braft	0.43 meters / 20 ft	**Motor Voltage**	48 V (8 batteries of 6V)
Maximum speed	9.66 km/h / 6mph	**Maximum Current**	40 A
Cruising speed	8.05 km/h / 5mph	**Batterie type**	Lead-Acid
Empty Weight	775 kg /1705 lbs	**Charger Voltage**	110 V — 120 V

RAND Boats ApS produces hybrid small yachts. They use electric engine system which offers reliability, fast speed, and low operating cost. It have more luxurious details and has better services, like a kitchen or a bathroom.

Overall Lenght	8.44 meters / ft in	**Outboard electric**	80 HP
Overall Width	2.055 meters / ft in	**Outboard gasoline**	150 — 300 HP
Braft	0.35 meters / ft	**Inboard gasoline or diesel**	150 — 300 HP
Weight ex. engine	from 1300 kg	**inboard electric**	Torqeedo DB 80 HP

Figure 5.3: Photography of the RAND Leisure 28. Source: <http://randboats.com/leisure28>

Last but not least, a company that not only offers low fuel consumption and the most innovative green technologies, but also a high level of comfort is *Greenline Yachts*. This company can show off of having produced in series the first hybrid yacht in the world and having the world's largest hybrid fleet, with more than 700 yachts sailing around the world. In 2010, the *Greenline 33* was the best-selling 10 meter boat in the world, that proof that people is really concerned about the climate change and is aware of all the advantages that can be offered by a hybrid boat.

Figure 5.4: Different models of *Greenline Yachts*. Source: <https://www.greenlinehybrid.es>

This boats are characterized by the solar panels and a bank of large-capacity batteries that allows to generate, store and use the power of the sun. Batteries can be charged through a plug in the tower of any berth or through the generator attached to the diesel engine. The *Oceanclass 65*, a 20.80 meters length overall, have a CAT C12 ACERT2 x 715 HP as a standard diesel engine and a generator of 16 kW. Without adding any extra diesel engine, the maximum speed at one third load in 22 knots. It also have an inverter/ charger to charge the batteries in any port.

6. CHARACTERISTICS OF THE YACHT

6.1. Main data

The ship chosen to carry out the present thesis is the Nomad 65 by Gulf Craft. Is a luxurious and comfortable yacht with three decks, as it can be seen on the Annex C : the fly bridge, the main deck with a saloon, a kitchen, a bathroom and a terrace, and the lower deck. This yacht have 3 cabins: the main room with his own bathroom and two more double cabins with one bathroom shared. On the other hand it have one cabin for the crew with a private bathroom and a private kitchen.

Figure 6.1: Photography of the Nomad 65. Source: Gulf Craft Inc

This long-range yacht is:

Length overall	20.00 meter
Beam	5.50 meter
Draft	1.40 meter

The principle characterizations are:

Displacement	32 t approx.
Fuel capacity	5680 l
Generator	28 kW, 50 Hz
Power options	2 x 857 kW, 2 x 597 kW, 2 x 533 kW

Finally, concerning the water:

Fresh water capacity	750 dm^3
Black water capacity	190 dm^3
Grey water capacity	190 dm^3

The main objective os this thesis is to transform the power system of this yacht into an hybrid one without losing any of it's characteristics and capacities.

6.2. Characterization of navigation area

The navigation area chosen is the Balearic Island in the Mediterranean sea. The port base is the port of Mahon in Minorca and the yacht will navigate across the islands. Accordingly, the study of the navigation zone will be split in two zones: when the yacht is in port and when it is navigating, It will be supposed that all the surrounding islands have the same characteristics. The two points, which will characterized the navigation area, are marked in red on the Figure 6.3.

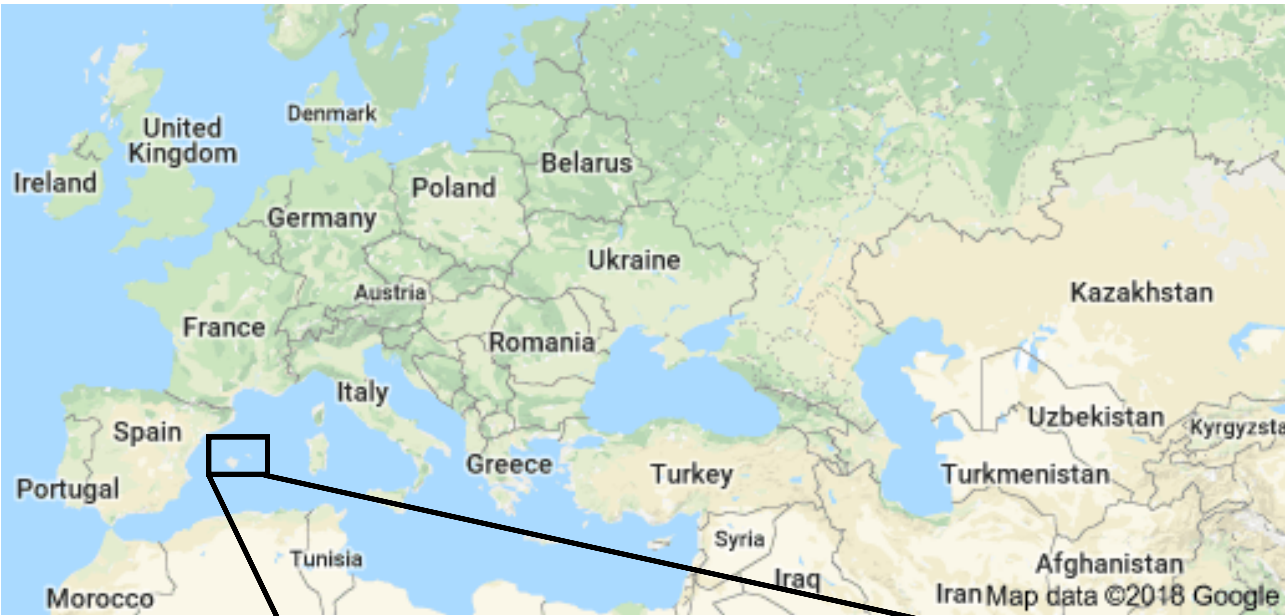


Figure 6.2: Map of Europe. Source: Google Maps.

Figure 6.3: Map of the Balearic Island and the points that characterized the navigation area. Source: Google Maps

6.2.1. Solar features

In order to know the solar radiation it will be used the computer software PVGIS. This computer software is a web platform organized by the European Commission which provides information about the solar resource anywhere in Europe. Using PVGIS, it is possible to obtain both monthly and daily data from the solar radiation that is anywhere in the territory. The next table (6.1) shows the monthly average solar radiation of the year 2017.

	GLOBAL IRRADIATION [kWh/ m^2.mth]	
MONTH	**PORT OF MAHON**	**CHANNEL OF MINORCA**
JANUARY	66.8	67.7
FEBRUARY	78.4	78.0
MARCH	129.9	130.2
APRIL	167.9	165.9
MAY	203.3	200.5
JUNE	218.8	219.6
JULY	231.8	233.2
AUGUST	191.2	196.4
SEPTEMBER	142.2	146.8
OCTOBER	104.3	107.1
NOVEMBER	69.7	69.8
DESEMBER	60.1	59.4
YEAR	**1664.2**	**1674.6**

Table 6.1: Monthly average solar radiation of the year 2017 at the Port of Mahon and at the Channel of Minorca. Source: PVGIS.

As it can be seen, the solar radiation that receives the Port of Mahon and the Channel of Minorca is very considerable, on the order of the 4.6 kWh/day/m^2 as annual average, a value that is located at the border point between the climatic zone of type III and type IV climate zone, accordingly to the CTE (Código Técnico de la Edificación), the Technical Building Code. He is considered, therefore, that it is a good place where to install photovoltaic panels.

6.2.2. *Wind features*

The website "Windfinter" provides information about wind in real time measurements and live webcams. It also provides wind forecasts and weather forecasts around the world. Above all, what is more interesting is the statistics they offered.

Month of the year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sept 09	Oct 10	Nov 11	Dec 12	Year 1-12
Direction of the main wind													
Probability of wind >= 4 Beaufort (%)	6	4	2	1	0	0	1	1	0	0	3	4	**2**
Average wind speed [kn]	4	4	4	5	5	5	6	5	4	4	4	4	**4**

Table 6.2: Wind average in the Port of Mahon. Source: Windfinter.

On this case the statistics are based on observations taken between 06/2016 and 03/2018 daily between 7 am and 7 pm local time.

This measures suggests that any type of renewable energy related with wind would be useless, in fact the maximum average wind speed is 6 kn in July when the probably of wind, more than 4 in Beaufort scale, is 1%. In contrast, the next table (6.4) shows that it could be interesting to study the possible profitability of application of wind energy to the yacht.

Month of the year	Jan 01	Feb 02	Mar 03	Apr 04	May 05	Jun 06	Jul 07	Aug 08	Sept 09	Oct 10	Nov 11	Dec 12	Year 1-12
Direction of the main wind													
Probability of wind >= 4 Beaufort (%)	32	50	46	48	40	43	49	41	43	43	47	45	**43**
Average wind speed [kn]	10	14	12	11	10	10	11	10	10	11	11	12	**11**

Table 6.3: Wind average in the Channel of Minorca

On this case the statistics are based on observations taken between 02/2011 and 03/2018 daily between 7 am and 7 pm local time.

At first sight it looks like there is a lot of wind on this area and clearly wind energy would be very useful for the yacht, but noting further the graphic this solution is not that obvious. In fact, the average wind speed is 11 kn. This is 4 in Beaufort scale and means that there is a moderate breeze. A more specific study should be performed to find out if it is worth it to make the installation of a wind turbine on the yacht.

7. ELECTRIC POWER DEMAND

All the following Chapter is an explanation of the Annex D: Electric power demand.

7.1 Listing elements that consume power

7.1.1 Habitation

Having in mind that the thesis concerns a luxurious yacht, there are some elements that have to be taken into consideration. The yacht needs to be well illuminated, both inside and outside. Moreover it needs to have a good air conditioning system and modern appliances, as well as fridges in all the outdoor areas in order to have cold drink everywhere while navigating. In addition modern TV's are installed in almost all the cabins and speakers all long the yacht. Finally, some secure cameras will be placed surrounding the yacht.

7.1.2 Propulsion

In this part will be taken into consideration all the elements that are necessary to run and move the yacht. Moreover, the lights to illuminate the yacht that are forced by the law will be also included on this section.

On the one hand it is important to know how much water a person consume in a day. According to the INE (Instituto Nacional de Estadísticas) each person consume 137 liters of water every day, the yacht is for 8 people that means that 1096 liters will be needed. In order to supply the water consumption the water maker WATER-PRO COMPACT S-90 from EcoSistems will be installed. This water maker offers an effective production of 60 or 90 liters per hour, this make a total of 1440 or 2160 liters every day respectively, so producing 60 liter per hour will be enough. If more water from the estimates is used, the water maker produces 25% more water.

Referring to the water issue, some pumps will be installed: fresh water pump, pressure taps pump for the shower, hot water circulation pump, water heater, greywater and wastewater pump. This pumps are used on bathrooms and for the kitchen.

In addition a mud pump and a bilge pump will be installed, as well as a fuel pump for the emergency engine.

On the other hand, a propeller and different elements for the anchoring will be needed. In fact the propeller will need a high level of energy.

7.1.3 Navigation

It is important to add navigation elements as the autopilot, computer, AIS, satellite antenna, weather station and the servomotor among others. All this elements will help the captain and the crew to have a more quiet, efficient and safe navigation. Apart from these systems it is necessary to alway have the equipment that follow safety regulations such as lifejackets.

7.2 Energy balance

To know how many energy consume each element some constants have to be considered: Ku, Kr and Ksr; Ku is the abbreviation for "Utilization factor", Kr for "Redundancy factor" and Ksr for "Load factor (or service factor)".

- Ku represents the relationship between the peak demand of an element and the nominal capacity. It is usual that consumers do not work to its nominal load, but with a lower, thus increase its useful life and reduce the maintenance needs. On this case Ku=1.
- Kr is the ratio between the maximum service electrical power and the maximum power installed for service. There are many redundant equipment in a ship. This factor takes into account that the total of existing equipment, only a part of them are operating. For example in a ship there are some pumps that are duplicated in case that one of them fail.
- Ksr can be defined as the relationship between the actual power consumed by an element in a period of time, and which would have consumed if the element had been running with his peak demand.

Taking to account the power of each element and all those factors a numerical table can be done. In order to know which will be the maximum energy consumed in a day, three cases will be stablished. Each case represent a different condition of the navigation.

	NAVIGATION [kW]	MANEUVERS [kW]	MOORED [kW]
HABITATION	7,43	7,43	7,43
ARRANGEMENT FOR PROPULSION	11,74	104,07	10,94
NAVIGATION	0,576	0,575	0,35
PROPULSION	1000	500	—
TOTAL	**1019,746**	**612,075**	**18,71**

Table 7.1: Comparison of the power needed according to the system of operation of the yacht

7.3 Total electric power demand

As it can be seen on the Table 7.1, when the yacht is navigating the power consumption is much higher than in another moment.. In order to choose the most appropriate solar panels, batteries and other types of energy sources, it will be taken to account this operation time. Accordingly, the total power is 1020 kW. Comparing with the other condition of navigation, maneuvering consumes much more power than the other cases.

The power consumption is expressed by hour; as it does not usually arise the case in which a yacht is one full hour maneuvering, it would not be needed to add a percentage of security.

8. Conception of hybrid power system

8.1. Solar panels

As it can be appreciate on Chapter 6, this yacht is supposed to navigate between the Balearic Island in Spain. There is a high quantity of solar energy on this zone, it is for this reason that some solar panels will be installed.

Currently the yacht have a convertible roof in the sun deck. This convertible roof will be transform in a normal roof and solar panels will be installed on it. In the Figure 8.1 there is a schema showing where will be the solar panels located. It is an area of 5,5x4,5 meters.

Figure 8.1: Schema about solar panels disposition. Source: photo from Gulf Craft.

Taking into account that the area for the solar panels is limited the selection of them is very important. First of all is necessary to choose between monocrystalline or polycrystalline. It is known that monocrystalline solar panels are made of a simple crystal of pure silicon, polycrystalline solar panels, instead, are comprise of multiple crystals. Monocrystalline modules can be recognized by their color and look uniform, indicating the purity of the Silicon. Is it true that monocrystalline modules are more expensive but they also are more efficient: offer greater power output, require least amount of space and work better in low light conditions.
It might be concluded from this that the best choice, for this case, is installing monocrystalline modules. After comparing different brands, the selected solar panel is Bosch Solar Module c-Si M 48. On the Annex E

there is he data sheet of this solar panel. This solar module measures 1,343x0,988 meters. At maximum 4 solar panels can be installed and will occupy almost all the available space.

Available space [m]	measure of 1 module [m]	space used for 4 modules [m]
5,5 x 4,5	1,343 x 0,988	5,372 x 3,952

Table 8.1: Space used by the solar panels

This solar panels can take 200 W peak power. Taking to account that 4 modules will be installed, the total power generate will be 0,8 kW.
In the table 6.1 it can be observed that the average global irradiation is always superior to all those values, so solar panels will be always working a full.
Observing the electric power balance on Chapter 7, it can be seen that the power necessary for the habitation section do not reaches 8 kW. It is for this reason that it has been decided to use all the power generate by the solar panels for lightning, air conditioning, appliances, ac power plugs and security.

On the other hand, it exists some solar panels that are flexible and people can walk on them. This modules will be installed on the floor of the deck sun and an the front part of the main deck, as it can be seen in the Figure 8.2.

Figure 8.2: Schema about flexible solar panels disposition. Source: photo from Gulf Craft.

This solar panels are less efficient, that means that more solar panels will be needed in order to produce the same amount of energy. In contrast they are more resistant, which allows walking on them. The chosen solar panel is from *SOLBIAN Flex* the *CP140Q*, the data sheet can be found on the Annex F with all the information needed.
Each solar panel have a dimension of 1,053x0,996 meters and produces 144 Wh. On the deck sun there is a free space of 2,7x1,2 meters and on the main deck of 2,1x1 meters. That means that in on the sun deck two solar panels can be installed and on the main deck only one.

If each solar panel has a power 144 W that means that the total power will be 432 W and the electric energy production during 10 hours, on the assumption of constant solar radiation, will be of 4,32 kWh.

8.2. Wind energy

In the Tables 6.1 and 6.2 it can be seen the wind average in Port of Mahon and in Channel of Minorca. From April to September, the months the yacht will be navigating, the average wind on the Port is 5 kn, however on the Channel is 10/11 kn. As a result, the use of wind energy will only be useful when the yacht is in the Channel of Minorca. While the yacht is navigating the wind energy will not be beneficial because it is going to be an effect called: apparent wind. The real wind is what is perceived when standing. As the ship moves it generates its own flow of wind due to its own speed, this generated wind joins or is subtracted to the actual wind and the resulting is what is called the apparent wind. It is for these reason that the air turbine will be working when the yacht is anchored out of the Port of Mahon. Accordingly, in a day the yacht can be an average of 5 hours anchored.

The brand Primus Wind Power have a marine turbine called Air X. It is special for marine environment because of the design and is intended for corrosive environments. This turbine produces 30 kWh of energy a month at 5,8 m/s. The wind speed operating range is between 3,6 and 22 m/s. On the case of the Channel of Minorca the average wind speed is 10/11 kn which is 5,14/5,66 m/s. In the Figure 8.3 there is a graphic showing the equivalence between the wind speed and the energy generated.

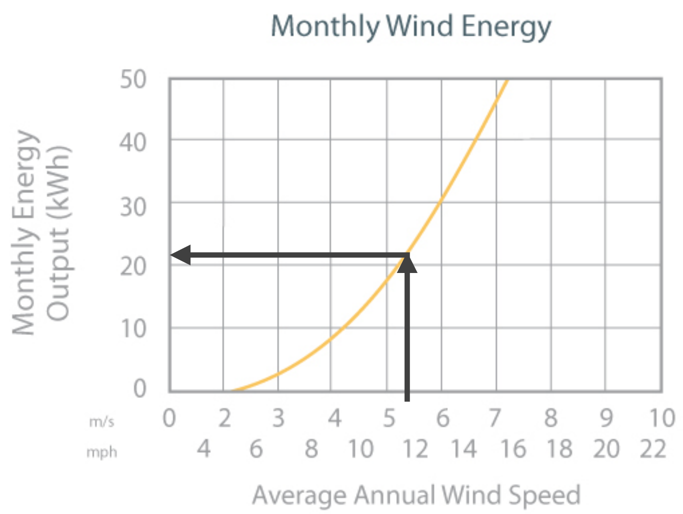


Figure 8.3: Graphic showing the Monthly energy output (kWh) in function of the average annual wind speed. Source: Primus Wind Power, data sheet of the Air X marine turbine.

According to the graphic above, the monthly energy output of the Air X while the yacht is in the Channel of Minorca is 21 kWh. A month have 30 days, so the daily energy output will be 0,7 kWh. As mentioned before it has been assumed that the wind speed is constant for 5 hours every day. It can be concluded that the generator has a power of 0,14 kW, so it can generate 0,14 kWh in one hour at the assumption that it works with nominal power.

8.3. Inverter

Both, wind turbine and solar panels, generate Direct Current. Batteries are always powered by Direct Current. On the other hand, energy consumers as home appliances ordinarily use Alternating Current. It is for these reason that an inverter will be needed.

It is determining to chose one that fits correctly. How much more energy needs to be converted, much bigger needs to be the inverter; in a yacht the space is limited this implies an accurate and correct election.

When choosing an inverter is important to look precisely at three aspects: the voltage that leaves the inverter, the peak of power that can support and the efficiency.

First of all it is necessary to know how many energy will be inverted in an hour. Obviously is not going to be the same energy each hour but all the calculations shall relate to when power is maximum. On the table below there is the addition of all the elements that generates energy in a sustainable way.

	Power data for each element [kW]	Number of elements	Energy production in an hour [kWh]
Solar panels	0,2	4	0,800
Flexible Solar panels	0,144	3	0,432
Wind turbine	0,14	1	0,140
TOTAL	**0,484**	**8**	**1,372**

Table 8.2: Total energy produced [kWh] and power data [kW] by renewable sources.

The inverter chosen on this case is a Phoenix Inverter by Victron Energy. It have a peak power of 1500 W and an efficiency of 91%, other characteristics can be found on Annex G. This inverter is able to convert into alternating current and continuous current, which is very important because the yacht have elements of both. Moreover the entrance pf power can be 12, 24 or 48 V, which will facilitate future selections.

This inverter have included an ECO mode which will switch to standby when the load decreases below a preset value, once in standby the inverter will switch on for a short period and if the load exceeds a preset level, the inverter will remain on. Furthermore, the company have an application both for phones and computers (VictronConnect) that provides access to status information, alarms and automatic user-configurable low-voltage shut downs.

8.4. Lithium-ion batteries

All the energy produced by the wind turbine and the solar panels will be stored in batteries. Usually, the energy produced will not be used at the same moment, so batteries play an important role. It has been proofed that is not possible to generate enough power only using renewable energies. Is for this reason that batteries can be also charged through a plug on the harbor. The battery chosen is The powerbank Lithium-ion battery solution by OmniPower. The Datasheet can be found on Annex H. This battery can store up to 6,4 kWh and have a maximum discharge power of 6,5 kW.

The case when the most power is required is maneuvering with a total power of 112 kW. That means that a total of 18 batteries will be needed to have enough power. The total power stored will be of 115,2 kWh.

This battery can only be used with 48 V inverter systems. Casually the inverter chosen before is a 48 V inverter system.

8.5. Main diesel generators

In case that the electric / diesel engine is still not enough, a engine is needed. The yacht Nomad 65 offers three different types of power options, as it can be seen in the Chapter 4. The three options are: 2 x 857 kW, 2 x 597 kW and 2 x 533 kW.

As the thesis is about an hybrid yacht the option which involves the minimum of energy will be selected. That means two engines of 533 kW each, a total of 1066 kW. The objective of the thesis is to run the yacht using the maximum renewable energies and the minimum of diesel oil. Moreover all the consumers are intended to be the most eco-friendly as possible; so if a little less power is provide by the engine it will not be an obstacle.

Two *Volvo Penta marine Genset* (in the Annex J there is a summary of the characterizations) are installed; that means the generator and the engine are together. Each one have a power of 500 kW, that means a total of 1000 kW.

In fact, other yachts with almost the same characteristics have this power system and offers a cruise speed of 20 kn, which is a favorable cruise speed.

As two engines have been installed there will not be necessary to install a third auxiliary engine.

Knowing that this engine consume 206 g/kWh, and that the energy produced by renewable energy is 1,372 kWh, the fuel saved can be easily calculated. Only one multiplication has to be done:

$$0{,}206 \times 1{,}372 = 0{,}282 \text{ kg}$$

That means a total of 0,282 kg of diesel oil are saved each hour thanks to the use of renewable energies.

8.6. Electric motor for propulsion

An electric motor for propulsion is installed before both diesel generators. It receives electric energy and gives mechanical energy that is used to make work the propeller. This Diesel generator needs to have the same power for propulsion than the power plant which is 1000 kW. An electric motor from WEG S/A is chosen that have an output of 1000 kW and an efficiency of 96,7%. The data sheet with all specifications and drawings are on the Annex J.

9. Power plan layout

The figure 9.1 shows a diagram of the power plant. It can be seen that the propeller can be moved by the engines or by the energy stored on the energy management. This energy management can received energy from batteries and charge them. Moreover the energy management can receive electricity from the photovoltaics panels (P.V.), the wind generator (W.G.) and the shore.

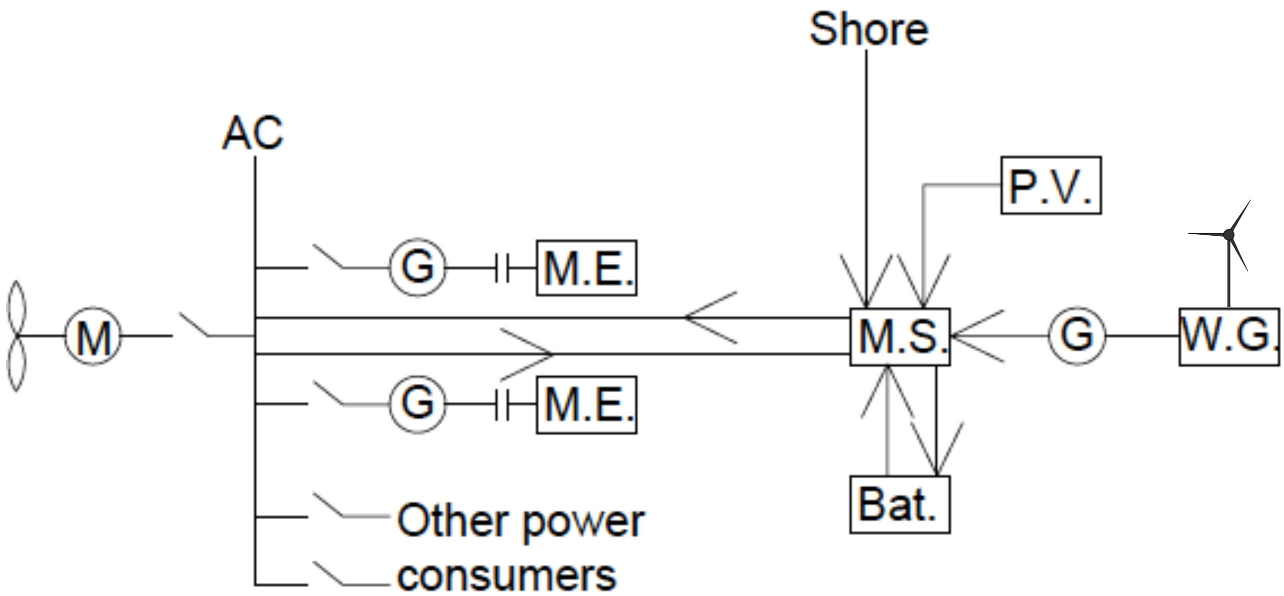
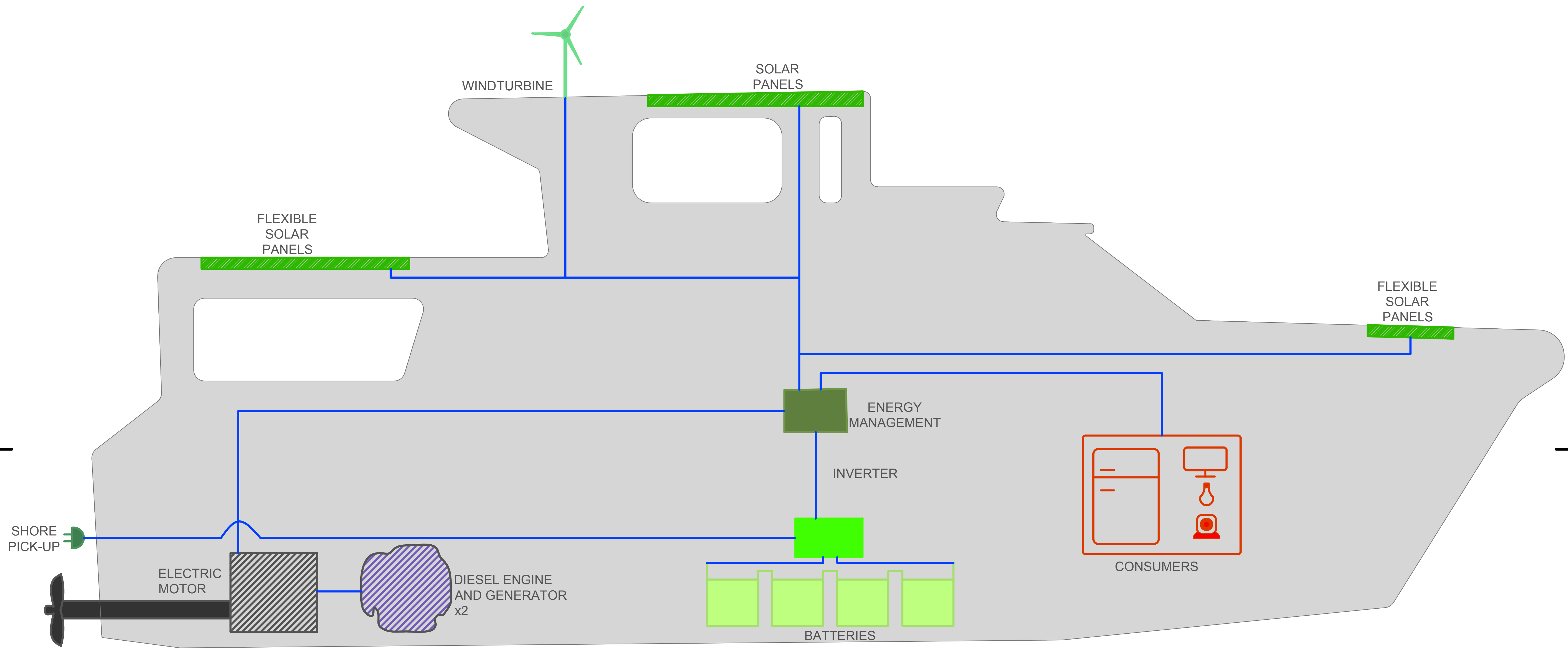


Figure 9.1: Diagram about the solution on the power plant of the Nomad65.

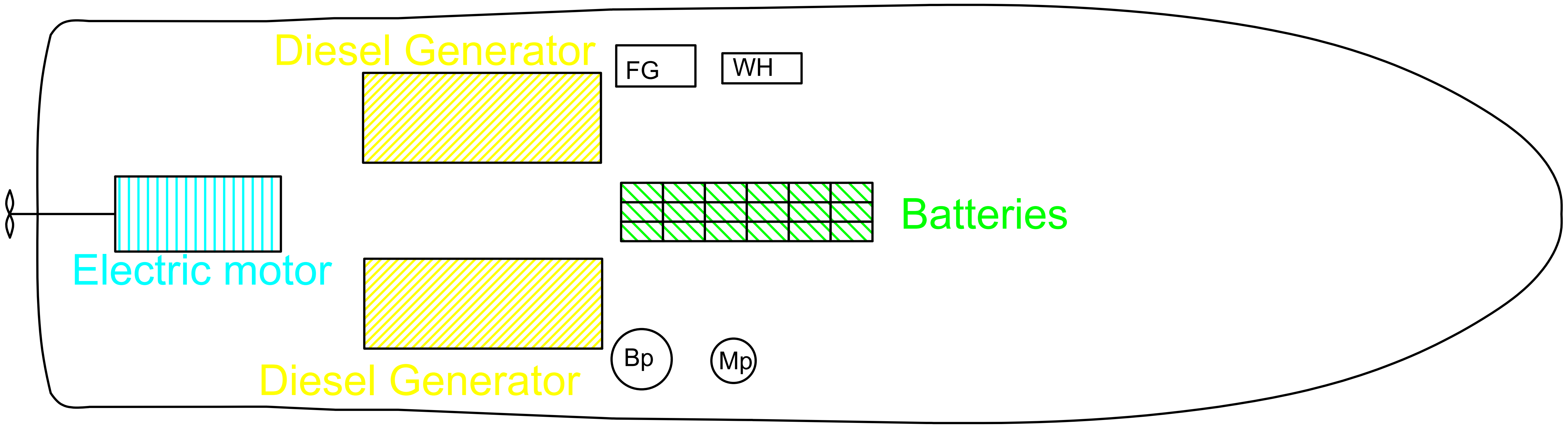
Otherwise, in the next page there is a power plan layout of the Nomad 65. It has been recreated the profile of the yacht so it is better to understand where are installed the renewable energies sources: on the sun deck and the main deck. On the roof of the sun deck there are 4 solar panels and the wind turbine, on the rear of the sun deck two flexible solar panels and on the front of the main deck 1 flexible solar panel.

There is also a top view showing where the elements are placed. This view is made in real scale with the yacht. It can be seen that all elements fits. It is important to put the electric motor at the center in order to be directly connect with the propeller. Stability is also an important issue, it is for these reason that it have to be the most symmetric as possible.

In brief, renewable energies sources, the shore pick-up and the diesel/electric generator generate electricity that charge the batteries. Before the batteries there is an inverter in order to eliminate electric differences. The generator is only used when there is no enough energy stored by sustainable resources. The energy is used for running the consumers and the propeller.



Department	Technical references	Type of document	State of the document			
Energy Engineering	UNE EN ISO	Scheme	Finished			
ZUT Szczecin Erasmus+ Program	Created by: Eva Roig	Title. Supplemental title. Electric plan layout of Nomad65	Naval Systems and Technology Engineering			
	Aproofed by: Mr. Zenczak		Rev. A	Date 14/06/2018	Language ingl.	Paper 1/1



Department: Energy Engineering	Technical references: UNE EN ISO	Type of document: Scheme	State of the document: Finished
ZUT Szczecin Erasmus+ Program	Created by: Eva Roig Aproofed by: Mr. Zenczak	Title. Supplemental title. Top view of the lower deck in scale of the Nomad65	Naval Systems and Technology Engineering Rev.: A · Date: 14/06/2018 · Language: ingl. · Paper: 1/1

CONCLUSION

The main objective of the thesis was to redesign the hybrid power plant of a 20 meter length yacht in order to make it more eco-friendly. The solution to the problem was solved installing solar panels and a wind turbine on the yacht in order to generate energy. The first conclusion made is that is possible to build a yacht more sustainable with the environment but, is it worth it with nowadays technology?

First of all is important to remark that the total energy produced by this renewable energies are a little insignificant: during the navigating not only the 0,1345% of the energy consumed by he yacht is elaborated by natural resources, otherwise while the yacht is moored or anchored an energy of 7,33% is produced. The percentage of energy produced in a sustainable way, as it can be proofed by numbers, is very minor. To understand it in a better, an average of 0,282 liters of diesel oil are saved every hour.

This energy is stored in batteries, which can also be loaded from a socket to port.

On the other hand, the installation of all these elements (batteries, solar panels, wind turbine) have a significant mass that should be taken into account for the stability of the ship.

Finally, it is important to know that the way the energy is generated depend on climate circumstances, what means that depending on the navigation zone the energy will have to be generated in a way or another. So a hybrid yacht design involves first a carefully study of the area which pretend to sail and implies that the yacht is limited to determinate zones.

It might be concluded from this that a hybrid boat is possible and there are on the market. In fact there are 100% hybrid boats that can work all time only with renewable energies but they are too small or are not useful to be used as leisure.This thesis has demonstrated that nowadays a 20 meter length hybrid yacht is not very profitable since the saved energy is very low and there are several disadvantages (weight, space).

In order to build a yacht of this characterizations which the makes a big difference further studies should be done concerning several subjects: how to generate more electricity with less space and how to store energy without using so much space.

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