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WYDZIAŁ TECHNIKI MORSKIEJ I TRANSPORTU

BACHELOR THESIS

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The possibility of solar energy use on ro-pax ferries

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ABSTRACT

Nowadays, the society is starting to worry about global warming and its consequences. Maritime transport is one of the mean of transport most used in the world of today. As every way to transport people and goods around the world, ships are emitting pollutant gases to the atmosphere and contributing to the mentioned global warming. Fuel-oil is also the main part of the ship's operating cost.

In this project there is proposed a solution in order to reduce the emissions of a ro-pax ferry by reducing its consumption of fuel-oil. The ship used is the ferry Côte d'Abâtre, that operates in the English channel, between Portsmouth and Le Havre. The solution used is the installation of solar panel in the upper deck of the ship. Using solar energy is possible to reduce the consumption of the fuel used in the generation of energy. The current development of solar technology is not enough to produce all the electrical energy that a large ship needs, but it is a solution that should be considered in order to reduce the consumption of fuel-oil and the emissions derived from its use.

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NOMENCLATURE

DWT - Death Weight Tonnage

GT - Gross Tonnage

Imp - current at Pmax

Impp - rated current

Isc - short-circuit current

Pmax - maximum power

Pnom - nominal power

rpm - revolutions per minute

Vmp - voltage at Pmax

Vmpp - rated voltage

Voc - open-circuit voltage

1. INTRODUCTION

In the world of today, the transport of people and goods is a critical issue. There are several ways to transport them, like air, maritime and terrestrial transport. Maritime transport is the most used of the three for many reasons. Ships are the mean of transport that offer greater loading capacity, compared with train, truck or plane. In general, maritime freights are more economical, especially in long distances. This is due to the capacity of ships against the one of the other means of transport. Ships are also less vulnerable to environmental conditions. The robustness, resistance and reliability of ships allows them to handle easily in complicated environments. Maritime transport is also more permissive with dangerous cargo than the other means of transport, sometimes is the only way to transport some specific materials or substances.

But maritime transport has its weaknesses too. In absolute terms, it is the most polluting mean of transport. Nevertheless, it is more efficient if we look the pollution by unit of load.The fuel used in maritime transport is of poorer quality than the one used in the other means of transport.While ships use fuel-oil, other means of transport use petrol or diesel-oil, which have been more refined than fuel-oil. It emits more Sulphur Oxides than conventional types of fuel. According a study of the year 2015, of the University of Rostock, which was entitled *How Ship Emissions Adversely Affect Lung Cells* and written by Professor Ralf Zimmermann, every year 60.000 Europeans die because of the pollution from maritime transport. Nowadays, because of the globalisation, every year there are more commercial lines between cities and the existing ones are increasing its frequency. This fact, leads to a situation of more pollution of the marine environment and more air pollution in cities which have harbour. For example, a moored cruise generates a pollution equivalent to 2.000 cars circulating in the same location. Currently, there are some cities in the world who change the taxes depending on the pollution of every ship, as Le Monde says.

Ro-pax ferries are ships that have to transport people as passengers, and also ro-ro cargo such as cars or trucks.A standard ferry could have capacity for 600 passengers and its corresponding cars. So, it needs a powerful power plant capable to provide enough energy needed for accommodation and for load decks. This energy is supplied by electric generators, which are feed with fuel-oil. Therefore, there is part of the air contamination that comes from generating electric energy. A standard ro-pax ferry could have two or three 2.000kW generators in order to produce 2.500kVA, 400V and 50Hz.

The aim of this project is to equip with solar cells a ro-pax ferry with the objective of generate the electric energy with solar energy and in this way try to save fuel-oil. Saving fuel-oil permits the operator of the ship to save money at the same time that it permits to pollute less the marine environment. Another challenge of this thesis is to know the extent of practice of using solar cells, to know how many fuel-oil it is possible to save. To achieve this goals, in this project there is a summary about how ships pollute the marine environment, focused in the air pollution, which provides from fuel-oil together with an explanation of the use of renewable energies in ships. The most used are wind, biomass and solar. To know how far it is possible to reach, there is a study of the actual state of art. To conclude, there is a proposal of an installation of solar cells in a ro-pax ferry. This installation wants to be capable of generating enough electricity in order to suppress the electric generator, save fuel-oil and pollute less the marine environment.

2- ENVIRONMENTAL IMPACT OF SHIPPING

Maritime transport is the most efficient mean of transport of goods across the world in pollution by unit of load. However, it produces a considerable environmental impact. This impact is caused by many factors. The main problems of maritime transport are: air pollution, vessel discharges, invasive species present in ballast water, and an affectation of marine life and habitats. Every ship-owner should manage this environmental impact by managing its own wastes, recycling or reusing them.

Commercial ships discharge ballast water, grey and black water and bilge water on a regular basis. With the discharge of ballast water, there is the risk to transfer invasive species from one ocean to another, with an affectation in ecosystems. The IMO Ballast Water Convention deals with problems associated in charge and discharge of ballast water in ports of all the world. This convention sets the maximum number of organisms allowed in discharge water. The discharge of grey and black water are regulated in the Annex IV of the MARPOL convention which is about prevention of pollution by sewage from ships.

2.1- Air pollution

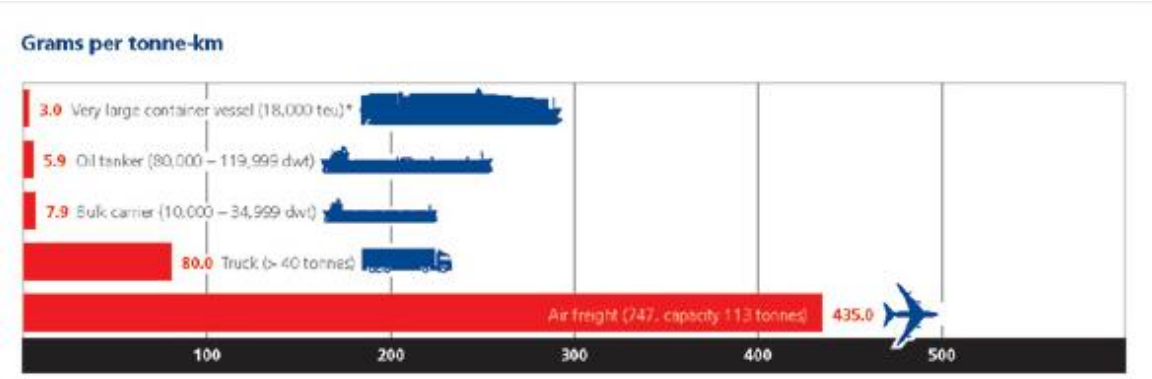
During their day-to-day operation, every ship emits Sulphur Oxides, Nitrogen Oxides and Carbon Dioxide to air. In areas with a great marine traffic, emissions from ships could be very significant. The Annex VI of the MARPOL convention deals about the prevention of air pollution from ships. This annex of the MARPOL was adopted in 2005 and entered into force in 2010.

2.1.1- Carbon Dioxide emissions:

Global warming is a very discussed topic nowadays, it means a rise in global temperature due to the climate change induced by all human activity. This activity emits greenhouse gases, who cause the greenhouse effect and the consequent global warming. The most emitted greenhouse gas is CO_2.

According the World Shipping Council, maritime transport emits 10 grams of Carbon Dioxide to carry 1 ton of cargo 1 kilometre. In this way, maritime transport is the mean of transport who emits less grams of Carbon Dioxide to carry 1 ton of cargo 1 kilometre. Moreover, every year the emissions of CO_2 providing from containerships decreases 6-8%, according Drewry Supply

Chain Advisors. Shipping companies need more efficient ships, in order to make their operation more economical. To give an example, in 2014, Maersk Line carried 7% more containers than in 2013 and reduced the emissions by container by 8%, according Drewry Supply Chain Advisors.



2.1- Comparison of Typical CO_2 Emissions Between Modes of Transport.

Source: International Chamber of Shipping. *ICS/Comparision of CO_2 Emissions by Diferent Modes of Transport*. (2017)

According the International Chamber of Shipping, around the 3% of the total global emissions have their origin in maritime transport. As it is shown in the graph, maritime transport emits from 3g/ton·km to 7,9g/ton·km. This value is well below the amount of CO_2 emitted by road and air transport, who emit 80g/ton·km and 435g/ton·km respectively.

Shipping companies are also interested in reduce their fuel consumption in order to reduce the operation cost of the ship. According the article *The Possibility if Renewable Energy Use on Ships*, written by WojciechZeńczak, fuels cost can reach the 80% of the annual ship operating budget.

Due to this reasons, it is necessary to find new design solutions. International Maritime Organization has developed a measure called Energy Efficiency Design Index (EEDI). EEDI (Energy Efficiency Design Index) came into force in the year 2011 and it applies in al ships launched after 2013. This index gives a numerical measure of the ship efficiency. This index depends on the nominal power on the engine axis, the fuel consumption of engines, the fuel type, the death weight in tonnes and the cruising speed of the ship.

2.1.2- Nitrogen and Sulphur Oxides emissions:

Nitrogen and Sulphur Oxides are chemical compounds that are formed in the combustion of the fuel-oil used to propel the ship. Both of them are responsible of the depletion of the ozone layer. SO_X emissions can also be the origin of many pulmonary diseases. Acidification and Sulphur Oxides may damage sensitive ecosystems, and affect biodiversity and growth of forests. They could also provoke acid rain, which causes significant damages to buildings and equipments. With regard to maritime affairs, NO_X and SO_X emissions are established in the Annex VI of the MARPOL convention.

From January 2020, the sulphur limit applicable to all fuels used in ships will be set as 0,5%. According the International Maritime Organization, in its AIR POLLUTION AND ENERGY EFFICIENCY Effective implementation of the 0.50% m/m sulphur limit under regulation 14.1.3 of MARPOL Annex VI, this reduce of sulphur emissions to the atmosphere from the world's fleet will involve a change in the operation of ships outside the Emission Control Areas (ECA). According the study *Reducing Sulphur Emissions from Ships*, signed by the International Transport Forum, ships generate approximately 5-10% of SO_X emissions, which means an average of 7-15 million tonnes emitted per year.

NO_X emissions are caused by an excessively high combustion temperate. This high temperature could be caused by a malfunction of the jacket cooler or by a heavy load on the engine unit. The quality of the fuel used affects the NO_X emissions too.

3- CONVENTIONS AND REGULATIONS

3.1- MARPOL

MARPOL is the name of the International Convention for the Prevention of Pollution from Ships. The aim of MARPOL is to prevent the pollution of the marine environment. This pollution is caused by the discharge of harmful substances and other pollutants into the sea.

MARPOL convention was agreed in two phases. The first one was written in 1973 as a result of the International Convention for the Prevention of Pollution from Ships. This convention was held by IMO as a consequence of the tanker Torrey Canyon accident in 1967. Five years later, in 1978, several tanker accidents forced IMO to convoke a Conference on Tanker Safety and Pollution Prevention. The result of this conference was MARPOL73/78. Since then, IMO has promoted six amendments of the convention in order to adapt it to modern times.

MARPOL convention includes six annexes, each annex deals with the prevention of pollution by a different origin. The annexes are:

-Annex I: Regulations for the Prevention of Pollution by Oil

-Annex II: Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk

-Annex III: Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form

-Annex IV: Prevention of Pollution by Sewage from Ship

-Annex V: Prevention of Pollution by Garbage from Ships

-Annex VI: Prevention of Air Pollution from Ships

For this thesis, the only annex that applies is the sixth.

-Annex VI: Prevention of Air Pollution from Ships

As its title indicates, the sixth annex of the MARPOL convention deals about the prevention of air pollution from ships. This annex focuses his attention in emissions of Sulphur Oxides (SO_X), Nitrogen Oxides (NO_X), and Carbon Dioxide (CO_2). Since its entry into force in 1988, the Marine Environment Protection Committee (MEPC), has been revising its validity. The main changes that MEPC has done are reductions of the global sulphur and nitrogen oxide percentage in the atmosphere. There isalso been the introduction of the emission control areas (ECAs), in order to reduce emissions of air pollutants in some areas.

ECAs are areas of the world that due to its peculiarity need a more strict protection. Those areas are: Pacific coasts of the United States and Canada, Atlantic coasts of the United States, Canada, France and the Gulf of Mexico, the Hawaiian Islands, the United States Caribbean Sea, the Baltic Sea and the North Sea.

According to the latest version of the MARPOL Annex VI, the global sulphur limit in fuel will be reduced from 3,50% to 0,50% before 1 January 2020. In ECAs, the limit of sulphur in fuel will be reduced to 0,10%.To achieve this goal, heavy fuel oil is allowed if it meets the sulphur limit, so distillate fuels are forbidden. It is allowed the use of scrubbers in order to clean exhaust gas.

Date	Sulfur Limit in Fuel (% m/m)	
	SOx ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020		0.5%

3.1: Fuel Sulphur limits.

Source: DieselNet: *Emission Standards: International: IMO Marine Engine Regulations.*(2018)

The Annex also includes progressive reductions in NO_X emissions from marine diesel engines. It sets the maximum emission for diesel engines depending on the engine speed, in rpm. As it is shown in the table, from 2016 in ECAs, the NO_X limit is Tier III. For n<130 engines is 3,4g/kWh. For 130<n<2000 engines, the limit is $9 \cdot n^{-0,2}$g/kWh, and for n⩾2000 engines, the limit of NO_X, in g/kWh is 1,96. Outside the ECAs, the limit of NO_X emission is Tier II. For n<130 engines, the limit of NO_X is 14,4g/kWh. In the case of an engine which works between 130 and 2000 n, its limit is $44 \cdot n^{-0,23}$. For n⩾2000 engines, the limit of NO_X is 7,7g/kWh. Tier I is outdated since 2000.

Tier	Date	NOx Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

3.2: NO_X Emission Control Areas.

Source: DieselNet: *Emission Standards: International: IMO Marine Engine Regulations.*(2018)

In the forth chapter of the MARPOL Annex VI, there are introduced two mechanisms to ensure an energy efficiency standard for ships. Those mechanisms are EEDI and SEEMP. EEDI (Energy Efficiency Design Index) is a parameter used to calculate the efficiency of the ship. It is calculated based on data about the ship and its engine. The formula used to calculate the EEDI index is:

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

Where: P means the 75% of the nominal power on the engine axis.

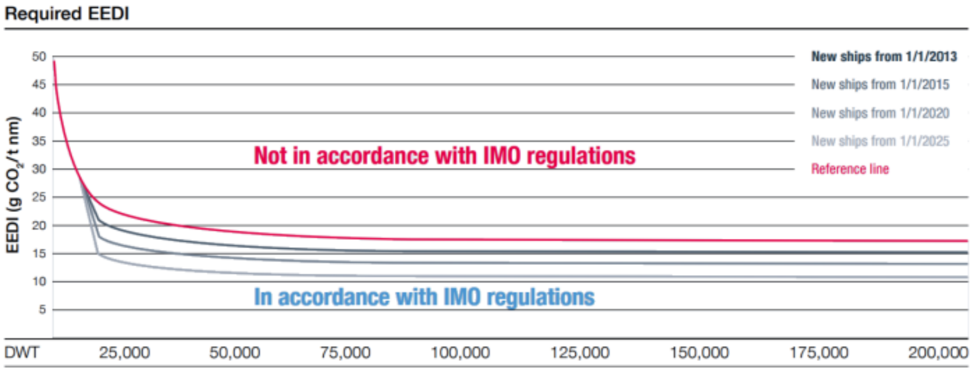
SFC means specific fuel consumption of engines

C_f is CO_2 emission rate based on fuel type

DWT means death weight in tonnes

V_{Ref} means cruising speed of the ship

EEDI provides the grams of carbon dioxide per ship's capacity-mile. It means that en energy efficient ship will have a small EEDI. MARPOL sets a maximum EEDI for every ship, depending on his launching year and DWT. The next graph shows the maximum EEDI allowed in every ship.



3.3: Maximum EEDI index.

Source: AMARINE. *EEDI and CO_2emission.*(2011)

SEEMP are the acronyms of Ship Efficiency Management Plan. SEEMP is a system that gives ship-owners tools in order to improve the energy efficiency of the ship. It is mandatory to have an efficiency management plan since 2013. Its philosophy is based in continuous improve of the energy efficiency of the ship. The method is similar than the one used in ISO:9001.To achieve this continuous improve, SEEMP uses the Plan-Do-Check-Act method. The ship-owner has to plan an energy efficiency plan. This plan should be put into operation and checked. During the operating phase, it has to be corrected in order to keep improving the energy efficiency of the ship continuously.

3.2- EU legislation

The European Union is legislating in order to reduce greenhouse gas emissions from shipping in European seas. This legislation has the goal of complement MARPOL convention. MARPOL convention is, most of all, based in SO_X and NO_X. The European directives are based in CO_2 emissions.

According the European Commission, emissions from maritime transport should decrease at least 40% from 2005 to 2050. To achieve this goal, The Commission has set out a strategy which consists in 2 steps. These steps are monitoring, reporting and verification of CO_2 emissions from large ship and a reduction of the greenhouse effect from the maritime transport sector.

The Regulation 2015/757 of the European parliament and of the council of 29 April 2015 deals with the monitoring, reporting and verification of carbon dioxide emissions from maritime transport. In this regulation, it is said that every ship over 5.000 gross tonnes operating in the EU territorial waters should have an exhaustive control on its CO_2 emissions. In this control there have to be monitoring of the combustion of all type of fuel. All ship travelling from an EU port to an EU port is forced to obtain, record, compile, analyse and document all data needed in order to determine the sources of the CO_2 emissions. Companies have to submit an annual report detailing all emissions caused by their ships and its sources.Those emissions can be monitored per voyage or on an annual basis. This reports have to include, part of the identification of the ship, the following parameters:

(a) port of departure and port of arrival including the date and hour of departure and arrival

(b) amount and emission factor for each type of fuel consumed in total

(c) CO_2 emitted

(d) distance travelled

(e) time spent

(f) cargo carried

(g) transport work

This reports are needed to be checked by an external verifier. The verifier shall asses the conformity o the emissions report. In case of favourable report, the external verifier has to emit a document of compliance which is required to carry on board.

The DIRECTIVE (EU) 2016/802 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 May 2016 relating to a reduction in the sulphur content of certain liquid fuels has as purpose to reduce the emissions of Sulphur Oxides originated in the combustion of certain types of liquid fuels. It says that Member States should ensure that heavy fuel-oils are not used in their territory if their sulphur content exceeds 1,00% by mass, and gas-oils whose content by mass exceeds 0,10%. According the Directive, Member States shall take measures in order to ensure that ships moored in port should not use any marine fuel with a sulphur content above 0,10% by mass. To achieve this, it is allowed to use emission reduction methods as scrubbers or other exhaust gas cleaning systems, , mixtures of marine fuel and boil-off or bio-fuels.

If any ship dos not fulfil this directive, Member States are able to apply penalties. Those penalties shall be determined by all Member States. The penalties determined shall be adequate, reasonable and dissuasive and may include fines calculated in such a way as to ensure that the fines at least deprive those responsible of the economic benefits derived from the infringement.

4- RENEWABLE ENERGY

Renewable energy is all energy obtained from continuing resources, such as the sun, plant crops, water or geothermal heat. In their book *Renewable Energy Sources*, John Twidell and Tony Weir define renewable energy source with the following definition:

Renewable energy is energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment.[1]

In this definition there are established three basic conditions to consider an energy source as renewable. The first condition is "naturally flow of energy". To consider an energy source as renewable, it is necessary that it has a natural origin. This excludes from the definition all sources that need any type of external action to initiate the supply of energy. To be considered as a source of renewable energy, a resource has to be persistent. Persistent not necessary means constant, a source of energy could be persistent but variable, for example, the sun. Such is the case of the sun, plant crops, water, from a river or from the sea and of geothermal heat. Finally, the sources of the renewable energy have to be present in the local environment. It is imperative that the source of the energy and their consumers are geographically close. In every transport of energy there exists a loss of it, so the source and the consumer of the energy should be closer.

In contrast, non-renewable energies are those that are limited in the nature. John Twidell and Tony Weir define them in their book *Renewable Energy Sources* in the following way:

Non-renewable energy is energy obtained from static stores of energy that remain underground unless released by human interaction.[2]

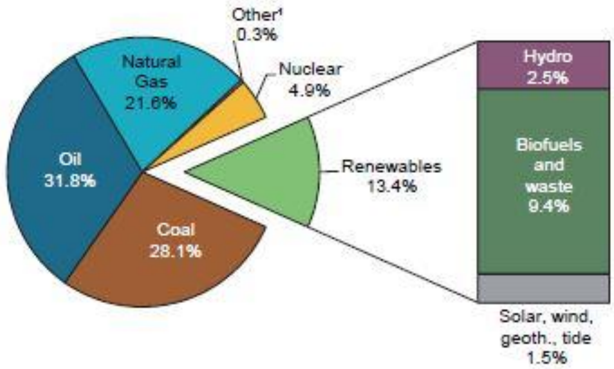
As it is said before, non-renewable energy source needs some alteration before they are capable to supply energy. Another disadvantage of non-renewable energy sources is that they are finite. It is no possible to be provided with them with endless.

According the International Energy Agency in their overview written in 2017, the 13,4% of the energy used in the year 2015 had was renewable energy. As it is shown in the graph 4.1, in the year 2017 the most used energy source was oil with a percentage of 31,8%, followed by coal,

[1]TWIDELL, John, WEIR, Tony. *Renewable Energy Resources*. Editorial Routledge. Abingdon, Oxon. (2015)

[2]Ibid

who contributed the 26,1% of the energy used.Natural gas contributed with the 21,6% of the energy. Finally, nuclear energy was the 4,9% of all energy used.

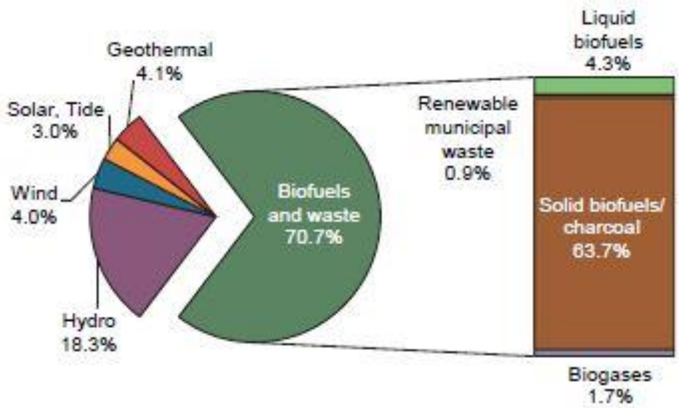


4.1: 2015 fuel shares in world total primary energy supply

Source: International Energy Agency. *Renewables information: Overview.* (2017)

If we take a look in renewable contribution, bio-fuels and waste were the source of the 9,4% of the energy used, hydro was the source of the 2,5%, and the last 1,5% was assumed by solar, wind and geothermic energy.

As can be seen in graph 4.2, the most used source of energy is bio-fuel, with contributing with the 70,7% of the total. Hydro energy contributes with an 18,3% of the total renewable sources. Geothermal, wind and solar energy are the lesser-used, contributing with 4,1%, 4% and 3% respectively.



4.2: 2015 product shares in world renewable energy supply

Source: Energy Agency. *Renewables information: Overview.* (2017)

Data mentioned previously is referred to the use of renewable energy in all type of industry. In shipping, the most used of renewable energy are wind, biomass and solar.

4.1- Wind

Wind has been used in shipping since at least 8000 years ago, according the article mentioned in chapter 2,*The possibility of Renewable Energy Use on Ships*. Square-rigged sails were used in the Nile river and in the Mediterranean in order to propel the ship taking advantage of wind. This type of propulsion had the limitation that it only could be used in the same direction than the wind. Gradually, this use of the wind as a type of propeller was evolving, it was used for maritime transport and military ships until new and more effective propelling ways were invented. Nowadays, wind as a form of propulsion is used for recreational purposes.

In modern ships, wind force is used to generate electrical energy or reduce the engine load. The most used forms of use the wind force are the ones explained below:

4.1.1- Sails

As it is said before, 8000 years ago square-rigged sails were taken into use in the Nile river, and little while after in the Mediterranean sea. Square sails were used to reduce the propulsion with oars, used until that moment. Years later, sails evolved and became triangular. Triangular sails had the advantage of being able to sail upwind, thanks at the Bernoulli's principle. Bernoulli's principle says that an increase in the speed of a fluid causes a decrease of its pressure. This depression around the sail causes the propulsive force.

In the world of today, sails are mostly used in recreational craft. In maritime transport are emerging fixed-sails (or wings). Fixed sails work under the same principle than soft-sails, with the difference that fist ones are made by rigid materials. The aim of fixed-sails is not to be the primary source of propulsion of the ship, its aim is to reduce fuel consumption.

According to the online magazine Motor Ship, fixed-sails could be made with aluminium or with a carbon fibre composite material. Eventually, fixed-sails can be equipped with solar panels, in order to generate electric power. This is the case of the water tanker shown in figure 4.3.

4.3: Water tanker equipped with fixed-sails

Source: Source: The Sydney Morning Herald. *On the horizon, solar-powered tankers to slake Sydney's thirst - Environment.*(2007)

4.1.2- Rotors

The Magnus effect is the cause of the apparition of a force in a body's surface when this body is rotating in cross-flow. According to the book *A review of the Magnus effect in* aeronautics, written by Jost Seifert, the Magnus effect is based in the superposition of the flow field and the rotation of the body who is rotating in the field. One side of the body rotates in the same direction than the flow field, adding the flow velocity and the rotating velocity. In the other side of the body both velocities are subtracting each other. According Bernoulli's principle, the higher velocity on one part of the body means a lower air pressure in that part of the body. This depression causes the Magnus force.

In October 1924, Anton Flettner constructed the first rotor ship, called Buckau. This ship had two cylinders of 15 metres who rotated by an electric propulsion. Nowadays, new rotor ships are appearing, like E-Ship 1, built by the company Enercon, which can be seen in figure 4.4. The disadvantage of using rotors is that is necessary to waste energy in order to make them rotate. The energy used in rotate cylinders is smaller than the propulsive energy saved.

4.4: E-Ship 1

Source: THIIINK. *Anton Flettner Rotor Vessel Ship Backau, now renamed Baden-Badenk*. (2017)

4.1.3- Kite

Another type of wind utilization is the use of kites. A kite is a type of sail which is rigged by control ropes, instead of being rigged by a mast. Due to this way of rigging, kite sails are only useful in downwind.In ships, the propulsion resulting from the use of kite sails is not enough to move the ship. The resulting propulsive force is used to reduce the engine's charge and save fuel.

SkySails system is the commercial name of kite sails for cargo ships developed by SkySails GmbH and Co KG. As reported by the digital magazine Ship Technology, SkySails' kites are attached to the ship by a rope system which is controllable from navigating bridge.Nowadays, this company produces kite sails for different types of ships, depending on their size and use.The company estimates that an average 87m cargo ship could save €300.000 a year in fuel.If 400 ships in all the world were using kite sails as an auxiliary propulsion system, the annual global emissions would decrease by 150 tons.

MS Beluga was the first carrier that used kite sails as propulsion system. Launched in 2007, it has 132m of length and 474TEU of capacity. In its initial test, it saved up to 2,5 ton/day of fuel using a 320m^2 kite sail. MS Beluga can be seen in the figure 4.5.

4.5: MS Beluga

Source: SHIP TECHNOLOGY. *MS Beluga SkySails* - *Cargo Ship* - *Ship Technology*. (2018)

4.1.4- Turbines

Wind turbines are electrical generators which take advantage of the wind present in their location. Their operation is quite simple, they produce AC by the use of an alternator.These electrical energy produced can be used to fed batteries or electrical engines.

The main problem that have wind turbines in ships can be affected by the velocity of the ship. If one vessel is sailing downwind, the wind influencing the turbine would be difference between ship and wind's velocity. As stated in the article *The possibility if renewable energy use on ships*, written by WojciechZeńczak, the power generated by a wind turbine is:

$$P = C_p \frac{\pi D^2}{4} \cdot \frac{\rho \cdot v_0^3}{2}$$

Where: P means power in kW

C_p is a power coefficient

D is the rotor diameter in m

ρ is mass density of the air in kg/m^3

v_0 is wind speed in m/s

As is can be seen in the equation, wind speed is the most influential parameter to determinate the power generated. Turbine diameter is also important given that it decides its area.

4.2- Biomass

Biomass is organic matter, matter who was once living and is now dead. Bio-fuel is biomass used as a fuel. Typically, biomass is made by wood, agricultural and animal wastes and from garbage.According the organization "Biofuel", from the United Kingdom, the most important difference between bio-fuels and fossil fuels is that bio-fuel can be produced in short period of time. Nowadays, bio-fuels made in a laboratory through chemical reactions are also considered as such.

Using biomass as fuel has the advantagethat it doesn't emit sulphursor nitrogen. The emissions providing from the combustion of biomass are water vapour and CO_2. The CO_2 emitted is the same that was once captivated by plants or wood during their live. Therefore, the global emission to the atmosphere is balanced.

In a ship, it is possible to install a biomass powered plant which operates using the wastes produced by crew and passage. In order to have enough waste, garbage and dark water, the ship would need to have a huge number of people, as is the case of a cruiser. In a cruiser, several tons of organic wastes are generated every day. According Albert Campuzano's bachelor thesis *The application of biogas energy as auxiliary source on a luxury cruise*, the installation of a biogas plant in a cruise would suppose a saving of fuel that would represent 1,7 million euro every year.

4.3- Solar

The use of solar energy on ships has three basic purposes. All three need the use of photovoltaic cells. The first two, consist in generating electrical energy form the solar radiation. This electrical energy can be used in the ship's power plant or can fed the electric motors used in the propulsion. The third application of solar energy on ships is its use to warm water on board.

The use of solar energy in shipping is relatively new. According to the already mentioned article *The Possibility of Renewable Energy use on Ships*, the first projects of ships using solar cells appeared 40 years ago. Nowadays, the most representative example of solar ship is catamaran Mobicat. Mobicat operates in the lake Bielersee, in Switzerland. It is capable to carry 150 passengers and sail in a speed of 7,5 knots. Their solar cells are installed in its roof. With a surface of $180m^2$, they are capable to produce 20kW of power. Mobicat can be seen in figure 4.6. Another example of solar ship is Solar Sailor, a water tanker who uses solar cells installed in fixed wings. Solar Sailor can be seen in figure 4.3.

4.6: Mobicat

Source: EMS Mobicat. *EMS / Mobicat / UnsereFlotte / Galerie / BSG - BielerseeSchiffahrt*. (2018)

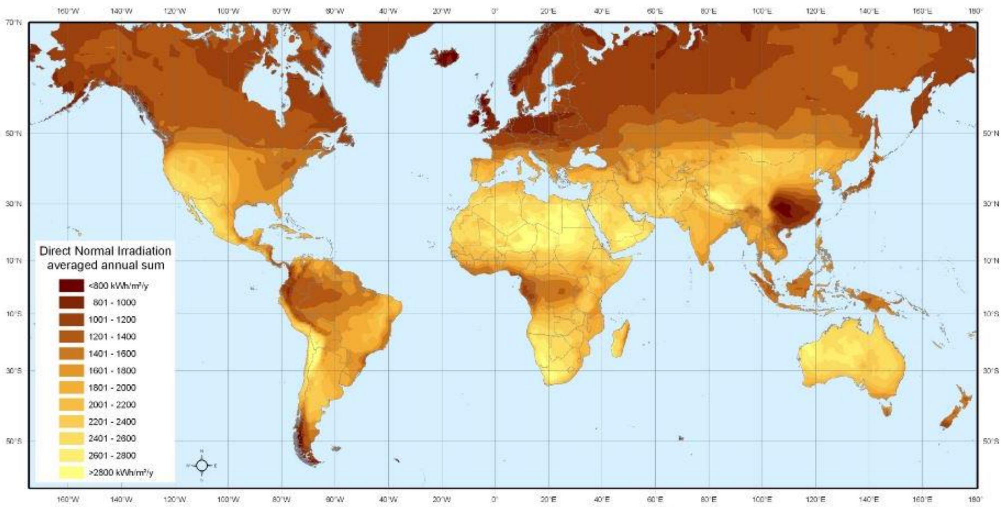
It is common for small boats or yachts to be equipped with solar cells. They are appropriate because of their low energy demand. Due to their small size and low sailing speed, small boats and yacht have power plants simpler than commercial vessels.

In commercial vessels, the demand of electrical energy is higher than in recreational crafts. Because of this, solar technology can only be an additional source of electrical energy. It can be used to reduce the load of the electrical generators. In general cargo carriers or in Ro-Ro vessels, it is easy to install photovoltaic cells. They can be located in their roofs or covers. The only case in which is not possible to install photovoltaic modules is in container ships. Containers are placed over the deck with anything over them. Due to this, it is not possible to install solar cells in container ships.

5- CHARACTERISTICS OF SOLAR RADIATION

Throughout history humanity has tried to seize solar energy for a variety of uses. Not for nothing, the sun is the main source of energy of the Earth. Solar energy is the cause of almost the energy that is used nowadays. It is the cause that allows life to take place in our planet. Therefore, is the cause that permits the existence of biomass. Solar energy is also the cause of the water cycle, evaporating it. Finally, wind is caused by solar energy too. Wind is the movement of the air caused by differences of atmospheric pressure.

Solar technology is based on taking a direct benefit of the energy providing from the sun. This energy can be used to generate electricity or to produce heat. Radiation is the used to denominate the amount of energy received by a solar panel measured in Wh/m^2. As it can be seen in the figure 5.1, the solar radiation received by a solar panel depends on the part of the Earth in where it is located. According the Photovoltaic Geographical Information System, which is part of the European Comission, the average solar radiation has a value of $1361W/m^2$.



5.1: Direct Normal Irradiation

Source: DLR InstitutfürTechnisheThermodynamik. *DLR - InstitutfüsTechnisheThermodynamik - Global Concentrating Solar Power Potentials.* (2005)

According to the figure, the most irradiated zones of the planet are Australia and the North of Africa. On the other hand, the less irradiated parts are the ones close to the Arctic. This information is of particular interest for the installation of any solar cell. Given that the energy produced by the solar panels will depend on the irradiation that they receive. In the case of a ship that sails all over the world, the energy that solar panels bring to the ship's electric power plant will be influenced by the region in where it is sailing. The region of the ship's operation may be considered in the design of its electric power plant.

When it goes through the atmosphere, the solar radiation experiences different types of absorption, dispersion and scattering. Due to this, the radiation that arrives to the Earth's surface is lower than the one that entries to the atmosphere. The main reason of this attenuation is the cloud cover. Atmosphere components, such as ozone, CO_2 or water vapour in suspension can also attenuate the solar radiation.

The maximum radiation available in any location will be the one received under clear sky conditions: without clouds and with a clean and dry atmosphere.

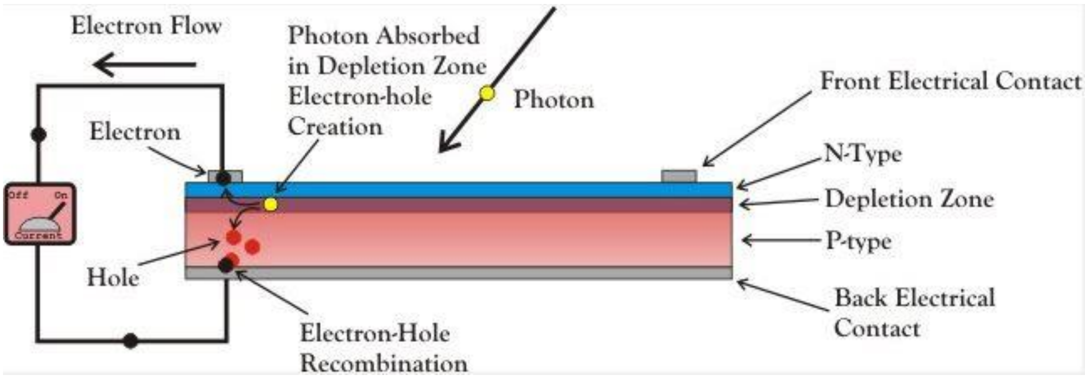
Solar radiation can be used in two for two different proposals: thermal purposes and electrical energy generation. In the case of the use of radiation for thermal purposes, radiation is absorbed by solar panels, who act as collectors. Those solar panels capture the radiation, that makes their temperature increase. A fluid circulating inside the collectors absorbs heat, which can be used or stored. This fluid is usually water, but it could be any other fluid with the right thermal proprieties. Electrical generation from the solar radiation is made using photovoltaic cells, as it can be read in the next subsection.

5.1- Principle of operation and construction of photovoltaic cells

A photovoltaic cell is a system which converts the energy of the sun into electrical energy. This conversion is made due to the photoelectric effect. Photoelectric effect is the emanation of electrons when electromagnetic radiation shines on a material.

In 1954, Bell Telephone Laboratories developed the first photovoltaic cells. This cells converted the energy providing from the sun into electrical energy. It was made of silicon and it efficiency was of 4%. The Bell solar cells delivered 50W of power per square yard, as it is stated in the article written by Lawrence L. Kazmerski:*The Bell Telephone Laboratories Discovery: Ushering in Our Modern Age of Solar Photovoltaics*.

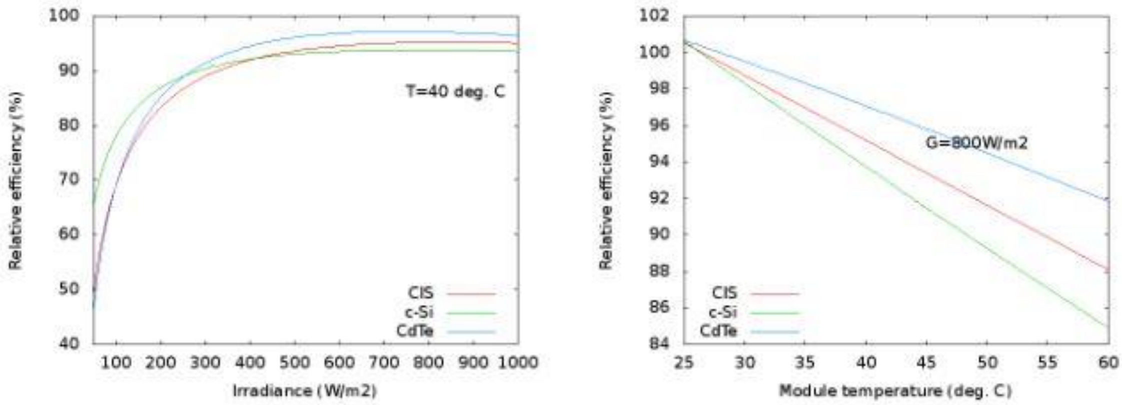
Solar panels are made of the integration of several solar cells. With the combination of them, it is possible to adjust the current and de voltage that they offer. Series association will increase voltage and parallel association will increase the current. A solar cell is a p-n junction with a large area. N-type material needs to be thin in order to allow light to pass throw it. N-type material has a high concentration of electrons, while p-type material has a low concentration of electrons. When both materials are arranged together there is a diffusion of electrons from the n-type material to the p-type material. This diffusion provokes a recombination of the electrons with holes on the p-type side. The result of the recombination is the appearance of a depletion zone around the p-n junction. When a photon is absorbed by the n-type material, it will eject an electron, conceiving a new free electron and a hole. The free electron and the hole will have enough energy to leave the depletion zone and enter in the n-type zone.



5.2: Principle of operation of a photovoltaic cell
Source: IMAGES SI. *How Photovoltaic Cells Generate Electricity*. (2017)

As it can be seen in the figure 5.2, if the n-type and the p-type zones are connected using a wire, electrons will flow through it creating a flow of electric current. Electrons are attracted to the positive charge of the p-type side, which works as an anode. the hole created by the electron is attracted to the cathode, the n-type part of the cell. When this happens, electrical neutrality is restored.

The efficiency of the photovoltaic cells depends on its temperature and on the solar radiation. Commonly, if the temperature increases, the efficiency decreases. According the Photovoltaic Geographical Information System, the efficiency of most module types is approximately constant for irradiances from $400W/m^2$ to $1000W/m^2$. If the irradiance is lower, the efficiency will decrease.



5.3: Relative efficiency of solar cells.
Source: Photovoltaic Geographical Information System. *JRC Photovoltaic Geographical Information System (PVGIS)* - *European Commission*. (2017)

The figure 5.3 shows the consequence of the temperature and the irradiation in a photovoltaic cell. Relative efficiency is the efficiency showed as a percentage of the capacity measured in the laboratory. In addition, over the years, the power given by the photovoltaic modules decreases. According the study of Jordan D. C. and Kurtz S. R. called *Photovoltaic Degradation Rates - an Analytical Review*, every photovoltaic module loses about 0,5% of power every year of operation. This involves that after 20 years of operation, the solar panel is giving the 90% of the power that offered when it was built. Photovoltaic Geographical Information System recommends to replace a module when it has lost the 14% of the initial power, that would suppose 28 years of operation.

There are three ways to use the electrical energy produced in a solar cell. The simplest of all consists in consuming the energy at the same that it is originated in the cell. The second way is to store the energy in a group of batteries. The most common way to seize the energy is a combination of the both explained before. With a mixed operation, a part of the energy is used at the same time that it is produced, and the rest is stored in batteries.

Nowadays, there are three types of photovoltaic modules on the market: monocrystalline, polycrystalline and flexible modules.

Monocrystalline panels are made of a single-crystal silicon. They are the most efficient panels, but also the most expensive to produce. This cells are made from a single silicon crystal, and they may be assembled in a rigid structure. The fabrication of this type of solar cells is based in the shaping of the sheets from silicon cylinders. This provokes an important loss of material, which is the cause of the elevate price of production of this type of cells. Their main advantage over polycrystalline cells is their efficiency. Monocrystalline cells have always an efficiency over the 15%, being current an efficiency of 20%. This elevate efficiency is due to the purity of the monocrystalline silicon.

Polycrystalline panels are made from a block of silicon which is consist of several silicon crystals. As the monocrystalline panels, they need to be assembled in a rigid structure in order to protect their integrity. In their production, there is not an important loss of material; they are made smelting the silicon in a squared mould. Due to this, their production price is not as elevated as in the case of monocrystalline panels. On the other hand, they offer an efficiency lower than monocrystalline panels. Polycrystalline panels offer an efficiency of 13-16%. Therefore, to offer the same electrical power, it is needed a larger polycrystalline panel than monocrystalline.

Flexible modules, already named thin-film, are made of amorphous silicon. Their main advantages are their low production cost, and their capacity of having different forms. Flexible solar modules are integrated, instead of installed in buildings or structures. That means that flexible modules can be part of a design, not just a liability. Flexible solar modules can be even coloured, so they can be adapted to singular structures. Their production cost can be four times lower than the production cost of a monocrystalline panel. As it is stated in the article *Flexible Solar Cells*, written by Rosaria Ciriminna, Mario Pagliaro and Giovanni Palmisano in the journal *Research Gate*, the efficiency of flexible solar modules can reach the 50%.

6- STATE OF THE ART

Once explained the use of renewable energy in ships, and the principles of operation of solar cells, in the following pages there are explained some examples of ships which use solar energy nowadays.

At this moment, operation cost of ships is depending of the fluctuations of the price of the oil. According to this, it would be normal that shipping companies wanted to escape from the dependence of the price of oil. Due to this, ship designers are looking at alternative powering options. One serious option of alternative powering is the option of renewable energy. As a result of this, in the last years are appearing new ships that use renewable energy as a main energy source. As ArnsteinEknes, the segment director for special ships at Det Norske Veritas, said in an interview conceded to the digital magazine *Motor Ship* in the March of 2012, there will be a concatenation of new ships using renewable solutions for their power plants.

- Aquaris Eco Ship

Eco Marine Power is a Japanese technology company of the field of the solar, wind and electric marine power and propulsion. In 2012, this company presented the project of the ship Aquaris Eco Ship. This large bulk carrier uses a system named with the commercial name Aquaris Marine Renewable Energy system.

Aquaris Marine Renewable Energy system is formed by rigid sails equipped with solar panels. By cause of the rigid sails, used as a secondary source of propulsion, the propulsion power required decreases, and the ship can save fuel. Solar cells are used to produce electrical energy, allowing to save fuel used in electricity generators. According to the company, an average installed solar power could be of 500kW, in a large bulk carrier. It may be achievable to reach the power of 1MW, if the efficiency of solar panels keep increasing in the next years. That could permit the ship not need to use auxiliary diesel generators, according Eco Marine Power. The company estimates that, depending on the number, size and configuration of the rigid sails, the vessel's annual consumption of fuel should be reduced in a 20%, with non favourable weather conditions. This would involve a reduction of the CO_2, NO_X and SO_X emissions.

In the table 6.1, there are detailed the main data of the Aquaris Eco Ship project.

LOA	240 metres	**Beam**	45 metres
Energy Sail Array	14 rigid sails	**Solar**	Aquaris MAS + Solar
Max Design Speed	17 knots	**Eco Speed**	12 knots

6.1: Main data of the ship Aquaris Eco Ship

Source: MOTOR SHIP. *The Motorship / Dawning of the age of Aquarius.*(2012)

- Planet Solar - Tûranor

Tûranor is a catamaran built by the Swiss company Planet Solar. This company was founded in 2008 with the aim of demonstrate that it is possible to use technologies avoiding the use of fossil resources. Tûranor is the largest solar ship in the world, and in 2010 became the first ship in round the world just using solar energy. It sailed 50.000 kilometres in 160 days, with an average velocity of 8 knots.

Tûranor has 35 metres of length, 23 metres of beam and is 6,3 metres high. Its design draft os 1,5 metres. The ship is equipped with 512m^2 solar cells which fed 6 blocks of lithium-ion batteries, that have a weigh of 8,5 tons. Solar panels generate 93,5kW of electric energy with a 22,6% of efficiency. The voltage of the batteries is of 388V and their capacity is 485 A·h for every battery, having an overall capacity of 2.910 A·h. Its autonomy in absence of sun is of 72 hours. The average speed of the ship is 5 knots, and its maximum speed is of 14 knots. This velocity is achieved by two electric engines, one in every hull, with a power of 60 kW each one that move two five bladed propellers . Their average consumption is 17 kW, added to the 3 kW used for life on board, the average consumption of Tûranor is 20 kW. The maximum capacity of the ship is 60 people, and it is equipped with 9 beds placed in 6 cabins. The total death weight tonnage of Tûranor is of 89 tonnes.

The figure 6.2 shows the aspect of the Tûranor.

6.2: Solar Sailor's Tûranor

Source: MER ET MARINE. *Le TûranorPlanetSolar se prépare pour des nouvellesaventures / Mer et Marine.* (2013)

- Sydney SolarSailor

Solar Sailor is a ferry that operates in Sydney, in Australia. It was the first solar powered ferry in all the world, it started to operate in the year 2000. Solar Sailor is powered by solar and wind energy by using eight mobile sails. Those sails are located over the main cabin and can be oriented in order to take the best advantage of the wind and the sun. The ship is able to carry up to 100 passengers.

As it can be seen in the figure 6.3, the inclination angle of the rigid sails can change depending on the location of the ship concerning the sun and the wind. Solar Sailor is also equipped with solar panels in its bow. In the case of none wind conditions, sails can be oriented horizontal, in order to exploit all the sun radiation. Solar Sailor creator, Dr Robert Dane predicted in an interview to the Australian magazine Eco Citizen that in fifty years almost all ships will be equipped with fixed-sails.

6.3: Sydney Solar Sailor

Source: ELUXE MAGAZINE. Hey Sailor! The Solar Sailor Boat. (2014)

Designed by academics from the University of Technology of Sydney, Solar Sailor has two electric motors as source of propulsion. Each motor has a power of 40 kW, rotate at a velocity of 900 rpm with an efficiency of 96% and have a weight of 113 kg. With this weight, they are much lighter than the average engine for similar ferries. The cruise speed of the ship is of 7 knots. With this moderated speed, the power demand is not elevated and batteries can be completely charged while passengers are embarking and disembarking.

Ship's designer Dr. Robert Dane estimates that Solar Sailor can safe an 5% of fuel from the solar power and another 20-40% from the wind power.

- NichioMaru

NichioMaru is a car carrier operated by the Japanese car manufacturer Nissan Motor Company. According the digital magazine Motor Ship, it is equipped with 281 photovoltaic cells that provide 50 kW of electrical power. This power is used in the illumination of ship's hold and crew quarters. The only engine is a single 13.280 kW MAN two-stroke diesel engine. This engine gives power to a five-bladed propeller. The main data of the ship NichioMaru can be seen in the figure 6.4.

As ship's operating company states, in every trip, NichioMaru saves 13 tonnes of fuel, reducing the CO_2 emissions in a 18%. The usual distance that the ro-ro covers in its average trip is of 1.800 km. This saving of fuel supposes an annual reduction of CO_2 emissions of 1.400 tonnes, as it is said in Motor Ship's article *Nissan goes greener with new car carrier*. According to this, NichioMaru emits 4.200 tonnes of CO_2 less than the average car carrier with a similar capacity

Length	169,95 m	**Beam**	26,00 m	**Draught**	6,50 m
DWT	7.200 ton	**GT**	11.514 ton	**Service speed**	21,2 kn
Load capacity:					
Completed vehicles	880 units	**Without truck trailers**	1.380 units	**With trailers**	115 units

6.4: Main data of the ship NichioMaru

Source: MOTORSHIP. *The Motorship / Nissan goes greener with a new car carrier.* (2012)

As it is said in the chapter 4 of this thesis, ro-ro carriers are the most suitable type of ship for using solar panels. Ro-ro vessels have their roofs or covers with free space to install photovoltaic cells, not as in the case of container ships, which carry containers in their decks without any type of cover.

-Auriga Leader

Another example of a solar ro-ro vessel is Auriga Leader, operated by the company Nippon Oil Corporation. Actually, Auriga Leader was the first cargo ship which used solar energy as a source of electrical energy. According the magazine Motor Ship, Auriga Leader is able to carry up to 6.400 car equivalent units. It is equipped with 328 solar panels, which generate 40 kW of electrical energy. With the use of the solar panels, the operating company expects to reduce the fuel consumption a 6,5%. This would suppose a reduction of 20 tonnes of CO_2 emitted every year.

Auriga Leader can be seen in the figure 6.5. Its length is of 199,99 m, its beam is of 32,26 m and it depth is of 34,52 m. The total death weight tonnage of the ship is 60.213 tonnes.

6.5: Auriga Leader

Source: MARINE IN SIGHT. *Auriga Leader - The World's First Partially Propelled Cargo Ship*. (2017)

In line with this examples, solar energy is an appropriate source of energy for ships. As Sydney Solar Sailor proved in 2000, the combination of different renewable energies can be enough to fed a moderate sized ship. If the ship is equipped with batteries of sufficient size, solar energy is also valid for ocean navigations, with its 2.910 A·h batteries, Tûranor circumnavigated the world just using solar energy. Nowadays, the main problem of solar energy for ships is that the energy that can be produced on board may be low. Ships can have solar energy as their only source of electrical energy if they dimensions are modest.

If solar energy is used in large carriers, it just can be an aid in electrical energy production. Large ships need a huge amount of electrical energy during their normal operation, so even having solar energy as a source of electrical energy, they need generators fed on fuel-oil. According to this, in the ro-pax ferry of this thesis, solar energy is just an aid for the electrical energy production. As NichioMaru and Auriga Leader confirm, it is possible to consider seriously solar energy for large ro-ro ships. These two examples corroborate that generators that use fuel are not the only valid form to get electrical energy. The ship utilized in this thesis is a ro-pax ferry, the reason of this is that, as said before, this type of ships have a free upper deck in where locate the solar panels. With the aid of those panels, the operation of the ship will consume less fuel-oil. This provokes the decrease of the ship's operating cost and pollution. However, the ferry will still need to use electrical generators, as its electrical demand is enough considerable.

7- CHARACTERISTICS OF THE FERY *CÔTE D'ALBÂTRE*

Côte d'Albâtre is a ro-pax ferry that operates in the English Channel, between Dieppe, France, and Newhaven, United Kingdom.It was built in 2006 in the Spanish shipyard Navairas ARMAS. It was originally delivered to the company Transmanche Ferries, and operated between Portsmouth and Le Havre. In 2015 it passed to be propriety of the company DFDS Seaways, and changed its route into the actual one, between Dieppe and Newhaven. Côte d'Albâtre has capacity for 650 people, considering passengers and crew and for 224 cars and 32 trucks. The external aspect of the ferry can be seen in the figure 7.1.

A ro-pax ferry is the result of adding ro-ro concept to a passenger ferry. An average ro-pax ferry can have capacity for 500 passengers and approximately 500 cars. This cars carried in the ferry are owned by the passengers, they are not commercial cargo. Typically, this type of ferries cover the route between two cities not far apart one from the other. Their routes are not usually longer than one day or two. This means that ro-pax ferries should have lodgement for their passengers.However, their accommodation is not as comfortable as the onethat can be found in cruisers, which cover extensive routes.

In the passengers zone of the ferry Côte d'Albâtre, there can be found different types of halls provided with bars and restaurants. It is also equipped for reduced mobility people, but not in all the accommodation zone. The adaptation has just been done in some of the halls of the ship. There are 50 cabins equipped with folding beds and private toilet.

7.1: Ferry Côte d'Albâtre

Source: Direct Ferries. *TransmancheFerriesCôted'Albatre opinie promu i przewodnika po promie.* (2018)

During the design of a ship, it should be considered the part of the world in where it sail. The zone in which Côte d'Albâtre navigates is the English Channel. The English Channel is the part of the sea that separates Great Britain and France. Therefore, both weathers should be considered. To this end, the meteorological organisations of both countries have been consulted: Med Office for the United Kingdom, and Météo France for France. In the figure 7.2, there can be seen the annual average values of the irradiation, rainfall, wind speed and temperature in Portsmouth and in Le Havre, the two ports where the ferry Côte d'Albâtre operates.

	Portsmouth (United Kingdom)	**Le Havre (France)**
Irradiation (kWh/m^2)	950	1100
Hours of solar radiation	1600	1617
Rainfall (mm)	800-1000	760
Wind (kn)	10-15	12-14,5
Temperature (ºC)	11	10,7

7.2: Average weather data in Portsmouth and in Le Havre (1981-2010).
Source: Med Office, Météo France. (2018)

As it can be seen in the table, the average irradiation of both ports is lower than the average in all the world, which is 1361 kWh/m^2. Le Havre has more solar radiation than Portsmouth, the reason of this is that Le Havre is located most southern than Portsmouth, so it is closer with the Equator, the most radiated zone of the planet. This is also related with rain, Portsmouth has more rainfalls than Le Havre, which means that it has less sunshine days. According to this, the ship will be capable to produce more electrical energy using its solar panels while being in the port of Le Havre. The average wind is very similar in both cities. This was an anticipated fact, both ports share the same sea and they are not far each other. The value of this average wind is not elevated, therefore it is not relevant in the design of the ship. The temperature value is also irrelevant, as the ferry will not sail in extreme temperatures, not cold and not even warm, the average temperature in its sailing region is anecdotal.

7.1- Main data

As it is said before, the ship used in this thesis is the ferry Côte d'Albâtre. In this sub-chapter, there is explained the main data of this ferry. The main data of the ferry Côte d'Albâtre can be seen on the table 7.3. All the data explained in this sub-chapter is obtained from the magazine *Ingeniería Naval*, in an article wrote the year 2006.

Main data	
LOA	142,45 m
Length between perpendiculars	125 m
Beam	24,20 m
Main deck's depth	8,35 m
Draught	5,70 m
DWT	2.900 ton
Propulsive power	2 x 9.450 kW
Service speed	22 kn
Autonomy	3.600 nm
Capacity (passengers + crew)	650 people

7.3: Main data of the ferry Côte d'Albâtre.

Source: IngenieríaNaval.*Entrega del ferry Côte d'AlbâtreenBarreras.* (2006)

The ship is classified by the society of classification Bureau Veritas, under the class Ro-Ro Passenger Ship. For the charge of cars and trucks, the ferry is equipped with 1.300 m of lineal space. This space can hold until 500 cars, or 31 trucks and 250 cars, divided in two decks. The charge and discharge of them is made between its two gates, which are located in the stern of the ship and have 16 metres of length and 7 metres of wide.

The anchoring and mooring is composed by two hydraulic grinders who can operate at two velocities. The first velocity, with a force of 14 ton, has de value of 15 m/min. The second velocity is 30 m/min and can reach 7 ton of force.

The propulsive system of the ferry is composed by two Wärtsilä four-stroke diesel engines. Those engines can produce a mechanic power of 9.450 kW everyone at 600 rpm. They are fed with fuel-oil. the axis line is formed by two gearboxes provided by 1.500 kW of power. The propeller of Côte d'Albâtre has 4.200 mm of diameter and rotates at 176 rpm.The steer system is composed by two hydraulic servo-rudders. Every one of them, moves a square bladed and semi-compensated rudder. There are two bow propellers which are fed with an electrical power of 1.300 kW each one.

The auxiliary machinery is composed by two shaft alternators that can produce 1.875 kVA of electrical power, with a voltage of 400 V and a frequency of 50 Hz rotating at 1.000 rpm. The emergency equipment is composed by a Liang-Man diesel engine which produces 270 kW of electrical power, with a voltage of 400 V and a frequency of 50 Hz too.

There is a cooler system for the auxiliary machinery which is formed by three fresh water electro-pumps that operates at a pressure of 0,25 MPa and a flow rate of 35 m^3/h, three plate coolers and four reserve electro-pumps that operate at 2 bar and with a flow rate of 200m^3/h.

The sea water circulating system is formed by three electro-pumps for the central cooling system that operate at 0,3 MPa of pressure and with a flow of 410 m^3/h, two electro-pumps for the fresh water generators that operate at 0,25 MPa and 50m^3/h, two for the steam condenser, with 2,5MPa and 100 m^3/h.

The fuel system is comprised of one fuel-oil transfer pump which operate at 0,4 MPa and 30 m^3/h, one diesel-oil transfer pump that offers 30m^3/h at 0,4 MPa, two fuel-oil purifiers with a capacity of 5.000 dm^3/h and one diesel-oil purifier with a capacity of 600 dm^3/h two purifiers for the main engines with a capacity of 2.800 dm^3/h, one for the auxiliary machinery with a capacity of 600 dm^3/h, one sludge pump able to offer 8 m^3/h of flow and that works at 0,4 MPa two reserve pump for the main engine and one transfer electro-pump for lube oil that gives a flow rate of 10m^3/h at a pressure of 0,4MPa.

There are is a gas burner in the steam system, able to produce 1.500 kg/h of steam at 0,69 MPa. In this system there are also two exhaust gas burners with a production of steam of 1.500 kg/h at 0,69 MPa each one. In the steam system there are also a steam condenser with a capacity of 2.000 m^3/h, two pumps that fed the gas burner and four circulating pumps.

In the fire-fighting system, there are two 70m^3/h and 0,8 MPa electro-pumps and one emergency pump with the same capacity. Outside the engine room, there is a sprinkles system that is equipped with an electro-pump that gives 100m^3/h and 0,8 MPa. The parking sprinkles have two pumps of 165 m^3/h and 0,8 MPa. The CO_2 system is formed by three independent systems, one in the engine room, another one in the kitchen exhauster and one in the placement of the emergency group.

The bilge system has two centrifuge pumps that offer a flow of 100m^3/h and 0,2 MPa and a bilge spacer with a flow of 5m^3/h. Outside of the engine room there are one bilge pump of 100 m^3/h and 0,2 MPa and one of 5 m^3/h and 0,2 MPa. The ballast system is comprised of two 150 m3/h and 0,2 MPa pumps with a remote actuator.

The compressed air system has two air compressors of 60 m3/h and 3MPa, two starting-air bottles for the main engines of 200 dm^3 at 3 MPa. One starting-air bottle for the auxiliary machine of 250 $dm^3$and 30 bar and another one of 125dm^3 and 7 bar. The compressor gives 90 Nm^3 at 7 bar.

The sanitary water system is formed by two fresh water generators of 20 t/day, one hydrophobic group of 1.000 dm^3 of capacity, one water purification system of 1.000 dm^3/h, two electro-pumps with a flow of 12m^3/h at 6 bar and another one of 1 m^3/h at 0,4 MPa. In the sanitary system there are also two steam heaters of 700 dm^3.

In the table 7.4 there can be seen the capacities of the exhaustible fluids on board.

Capacities	
Fuel-oil	660 m^3
Diesel-oil	80 m^3
Lube oil	38 m^3
Fresh water	104 m^3
Ballast water	1.550 m^3

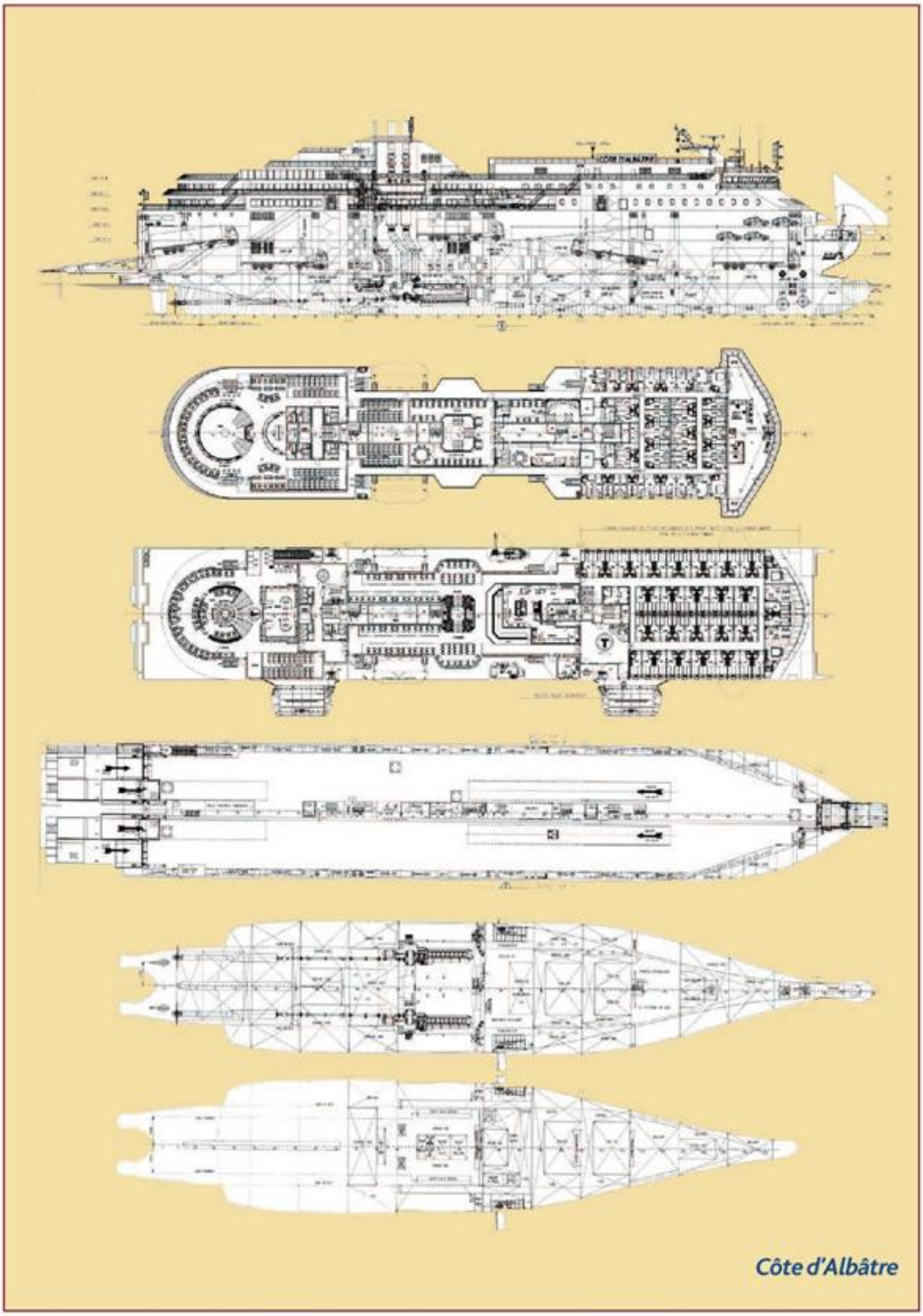
7.4: Capacities of the ferry Côte d'Albâtre.

Source: IngenieríaNaval.*Entrega del ferry Côte d'AlbâtreenBarreras.* (2006)

The lifesaving device is able to attend 560 people on board. To achieve this objective, it is comprised of four life rafts, able to carry 101 people every one. In addition, there are four more life rafts able to carry 51 people every one. In order to follow the French maritime legislation, three of this rafts are equipped with a radar reflector.

The electronic and communication system is composed of one megaphone of general alerts on board, two telegraphs, one of them used for the communication between the navigation bridge and the engine room. In this system there are also forty-eight telephones for intern communication on board, a general alarm system independent of the fire-fighting system and remote indicator of the levels of every tank. All navigation equipments, GMDSS and AIS where givn to the shipyard by the brand Crame.

In the next page it can be seen the deck's plan of the ferry Côte d'Albâtre.



7.5: Deck's plan of the ferry Côte d'Albâtre.

Source: Ingeniería Naval. *Entrega del ferry Côte d'AlbâtreenBarreras*.(2006)

8 - RULES FOR DETERMINING THE ELECTRICITY DEMAND ON THE SHIP

The majority of the auxiliary services of a ship use electrical energy in its operation. The electrical system of the ship should be designed in order to be able to fed all those services. The services which use electrical energy are pumps, purifiers, the illumination or the navigation equipments, between others.

The most typical electrical system on an average ship would be comprised by generators, who produce the electrical power -in the case of this thesis helped by solar panels- the main switchboard, from where the energy is distributed to all the services, batteries and the consumers of the electrical energy.

The main switchboard is the main distribution equipment of the electrical energy on board. It should be located close to the electrical generators, in order to not lose the electricity during the transport. The energy that arrives to the main switchboard is distributed to the consumers or to auxiliary switchboards. Batteries are the devices that are able to store electrical energy using one or more electrochemical cells. In large carriers, batteries are used to fed the emergency systems, and some CC devices. In small boats, batteries can be used to fed all the electrical demand on board. The capacity of a battery is measured in A·h and is calculated with the following expression:

$$C = I \cdot h$$

Where: C means capacity in A·h

I means electric current in A

h means time in hours

In Europe, the electrical power generated has a voltage of 380 V and a frequency of 50 Hz, in AC, in the case that the ship was built following the American rules, the electricity produced on board would have a voltage of 440 V and a frequency of 60 Hz. In the case of one system operating in CC, it would have a voltage of 12 or 24 V.

In the design of the electrical system of the ship there are two steps: the conceptual project, and the detailed project. In the conceptual project, the technical specifications are defined, the main consumers of electricity are identified and there is an estimated calculation of the electricity demand in different operating conditions. In the phase of the detailed project, all the consumers are finally known, and also their power demands. Thus, the electrical generators can be dimensioned. In this phase of the design there is also a calculus of the flow of loads and of the possibility of short-circuits.

The energy balance is the genuine form of calculate the electricity demand of a ship. In is used to determinate the electrical power demand in every condition of operation in order to dimension the sources of electrical energy. The energy balance consists in the sum of all the electrical power used in every operation of the ship.In order to avoid the over-sizing of the electrical generators, there are used some coefficients. These coefficients are used because not all the consumers are used at the same time and at its maximum power. The objective of the energy balance is to fit the most with the reality of the operation of the ship. The three coefficients used in this thesis are explained below:

- Utilisation rate, K_U: Is the percentage of the maximum demand of the element and its nominal capacity. It is not strange that some consumers on board work in a demand lower than its nominal capacity. This is made in order to extend its useful life. The nominal power of every consumer will be multiplied with the utilisation rate in order to count only the real power in the energy balance.

- Redundancy rate, K_N: Is the rate between the number of items installed for one porpoise and the ones used. In a ship, every item has a spare one ready to be used in case of breakage. Due to this coefficient, the standby items are not counted in the energy balance, the only calculated are the ones working at the same time.

- Service factor, K_{SR}: Is the rate between the real power consumed by an item and the power that it would have consumed if it had been working at its maximum demand. This coefficient is related with the utilisation rate, as it is based in that the items are not working at its maximum demand of energy.

The most common way to do an energy balance is the realisation of a table including a list all the electrical energy consumers, their nominal power consumption, the number of items on board and the three coefficients explained before. With this information, it is possible to calculate the energy demand of the ship in different operation conditions. In this thesis, the operation conditions considered are: navigation, manoeuvre, charge or discharge and moored. All of these four conditions will have different energy requirements. There can also be considered the difference between day and night, considering the electrical power used in illumination or in the navigation lights.

Once done the energy balance the electrical generators can be choose. They have to be able to fed all the operating conditions, with a security rate, usually 10-15%. As a rule, the system have to have enough items in order to be capable to respond to the different needs of the ship in every situation with the best efficiency. To achieve this, the most common solution is to equip the ship with at least three generators. If the power demand is the 25% of the maximum, it would be better to have one generator offering this energy at 75% of its demand than three offering the 25% of their capacity. The system has to be capable to overcome the failure of one of the generators, this is another reason for the installation of more than one generator.

8.1- Energy balance

The energy balance of the ferry Côte d'Albâtre has been done following the process explained before. There have been considered the equipments and the systems explained in the same source that in the chapter 7 of this thesis, the article *Entrega del ferry Côte d'AlbâtreenBarreras*, of the magazine Ingeniería Naval of the year 2006. In the next page, there is shown the energy balance of Côte d'Albâtre.

As it was expected, the operating condition with the highest electricity demand is the manoeuvre condition. The reason of this is that in while the ship is manoeuvring, it is using the bow propeller. Bow propeller is fed with en electric engine, due to this, when it is being used, the electrical demand is higher than in another operating condition. In this case, the maximum power demand is 2914,29 kW.

After that, the next operating conditions which have more power demand are the navigation condition and the charge or discharge condition. Their power demand is 325,91 kW and 257,25 kW respectively. The reason of their lower power demand, compared with the manoeuvre condition is that the bow propeller is not being used. The demand in this two situations is similar, the main different thing is that in the navigation condition there are being used all the cooler and fuel systems. On the other hand, in the charge or discharge operation, ballast water pumps are being used.The operation condition with the lowest electrical power demand is the moored one, with a demand of 128,84 kW. In this condition of operation, the systems more used are the sanitary water and the fire-fighting one. This operating condition is not critical, given that when the ship is moored it is connected to the electrical services of the port.

RO-PAX FERRY

										NAVIGATION		MANOEUVRE		LOAD ON/LOAD OFF		MOORED	
Service	Sub-system	Equipment	Units	Service units	Electricla Power (kW)	Installed Electrical Power (kW)	Ku - Utilisation rate	Kn - Redundancy rate	Demanded Electrical Power (kW)	Ksr - Service Factor	Estimated Electrical Power	Ksr - Service Factor	Estimated Electrical Power	Ksr - Service Factor	Estimated Electrical Power	Ksr - Service Factor	Estimated Electrical Power
Propulsion	*Manoeuvre*	Bow propeller	2,00	2,00	1300,00	2600,00	1,00	1,00	2600,00	0,00	0,00	1,00	2600,00	0,00	0,00	0,00	0,00
Cooling	*Auxiliary machinery*	Fresh-water electro-pump	3,00	2,00	35,00	105,00	1,00	0,67	70,00	1,00	70,00	0,80	56,00	1,00	70,00	0,00	0,00
Cooling	*Auxiliary machinery*	Electro-pump	4,00	0,00	35,95	143,78	1,00	0,00	0,00	1,00	0,00	0,80	0,00	1,00	0,00	0,00	0,00
Sea water circulation	*Central cooling*	Electro-pump	3,00	2,00	35,95	107,84	1,00	0,67	71,89	0,70	50,32	0,70	50,32	0,40	28,76	0,00	0,00
Sea water circulation	*Fresh-water generator*	Electro-pump	2,00	1,00	35,95	71,89	1,00	0,50	35,95	0,70	25,16	0,70	25,16	0,40	14,38	0,00	0,00
Sea water circulation	*Steam condenser*	Electro-pump	2,00	1,00	35,95	71,89	1,00	0,50	35,95	0,70	25,16	0,70	25,16	0,40	14,38	0,00	0,00
Fuel	*Fuel- oil transfer*	Transfer pump	1,00	1,00	5,00	5,00	1,00	1,00	5,00	0,80	4,00	0,10	0,50	0,10	0,50	0,10	0,50
Fuel	*Diesel-oil transfer*	Transfer pump	1,00	1,00	7,35	7,35	1,00	1,00	7,35	0,10	0,74	0,80	5,88	0,10	0,74	0,10	0,74
Fuel	*Purifiing*	Fuel-oil purifier	2,00	1,00	18,00	36,00	1,00	0,50	18,00	0,60	10,80	0,10	1,80	0,10	1,80	0,10	1,80
Fuel	*Purifiing*	Diesel-oil purifier	1,00	1,00	4,00	4,00	1,00	1,00	4,00	0,10	0,40	0,60	2,40	0,10	0,40	0,10	0,40
Fuel	*Purifiing*	Main engines purifier	2,00	2,00	2,00	4,00	1,00	1,00	4,00	0,80	3,20	0,20	0,80	0,10	0,40	0,10	0,40
Fuel	*Purifiing*	Auxiliary machinery purifier	1,00	1,00	2,00	2,00	1,00	1,00	2,00	0,20	0,40	0,80	1,60	0,10	0,20	0,10	0,20
Lubricating oil	*Oil transfer*	Electro-pump	1,00	1,00	2,00	2,00	1,00	1,00	2,00	0,10	0,20	0,10	0,20	0,10	0,20	0,10	0,20
Steam	*Gas burner*	Pump	2,00	1,00	35,00	70,00	1,00	0,50	35,00	0,30	10,50	0,30	10,50	0,30	10,50	0,30	10,50
Steam	*Steam circulation*	Pump	4,00	2,00	0,30	1,20	1,00	0,50	0,60	0,20	0,12	0,70	0,42	0,50	0,30	0,00	0,00
Fire-fighting	*Circulation*	Pump	3,00	2,00	17,50	52,50	1,00	0,67	35,00	1,00	35,00	1,00	35,00	1,00	35,00	1,00	35,00
Fire-fighting	*Sprinkles*	Electro-pump	1,00	1,00	19,00	19,00	1,00	1,00	19,00	1,00	19,00	1,00	19,00	1,00	19,00	1,00	19,00
Fire-fighting	*Parking sprinkles*	Electro-pump	2,00	1,00	19,00	38,00	1,00	0,50	19,00	1,00	19,00	1,00	19,00	1,00	19,00	1,00	19,00
Bilge	*Bilge pumping*	Pump	3,00	2,00	11,00	33,00	1,00	0,67	22,00	0,80	17,60	0,20	4,40	0,00	0,00	0,00	0,00
Bilge	*Bilge separator*	Bilge separator	1,00	1,00	1,00	1,00	1,00	1,00	1,00	0,80	0,80	0,20	0,20	0,00	0,00	0,00	0,00
Ballast	*Circulation*	Pump	2,00	1,00	27,00	54,00	1,00	0,50	27,00	0,20	5,40	1,00	27,00	1,00	27,00	1,00	27,00
Compressed air	*Compressed air*	Air compressor	2,00	1,00	10,50	21,00	1,00	0,50	10,50	0,40	4,20	0,40	4,20	0,20	2,10	0,20	2,10
Sanitary water	*Fresh-water generator*	Fresh-water generator	2,00	1,00	0,80	1,60	1,00	0,50	0,80	1,00	0,80	1,00	0,80	1,00	0,80	1,00	0,80
Sanitary water	*Circulation*	Electro-pump	2,00	1,00	5,40	10,80	1,00	0,50	5,40	1,00	5,40	1,00	5,40	1,00	5,40	1,00	5,40
Sanitary water	*Circulation*	Electro-pump	1,00	1,00	5,40	5,40	1,00	1,00	5,40	1,00	5,40	1,00	5,40	1,00	5,40	1,00	5,40
Navigation	*On board*	Telephone	48,00	48,00	0,00	0,16	1,00	1,00	0,16	0,40	0,06	0,60	0,10	0,00	0,00	0,00	0,00
Navigation	*On board*	Telegraph	2,00	2,00	1,00	2,00	1,00	1,00	2,00	0,60	1,20	1,00	2,00	0,50	1,00	0,20	0,40
Navigation	*External communication*	AIS	2,00	2,00	0,03	0,05	1,00	1,00	0,05	1,00	0,05	1,00	0,05	0,00	0,00	0,00	0,00
Navigation	*External communication*	Radar	2,00	2,00	5,50	11,00	1,00	1,00	11,00	1,00	11,00	1,00	11,00	0,00	0,00	0,00	0,00
									Electrical Power Demanded (kW		325,91		2914,29		257,25		128,84

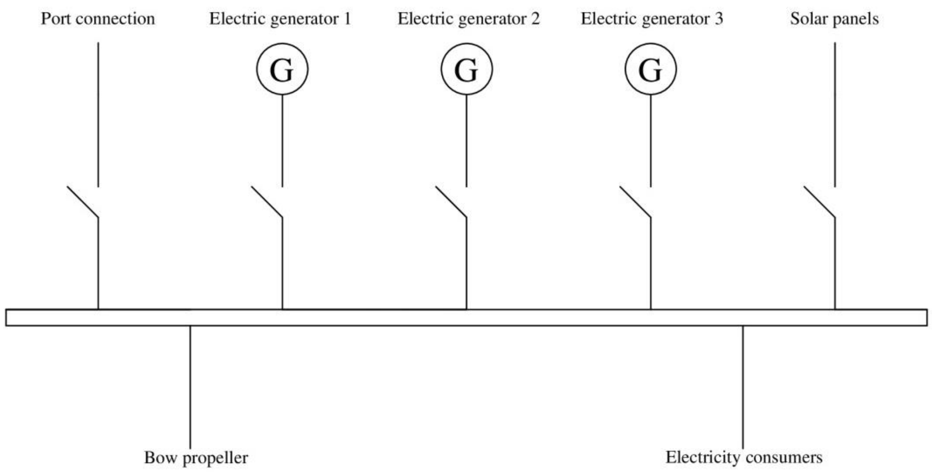
8.1: Energy balance of the ferry Côte d'Albâtre

Source: The author. (2018)

9- SOLUTIONS OF THE SHIP'S ELECTRIC POWER PLANT

Once calculated the energy balance of the ship, there should be designed the ship's electric power plant. The ship's power plant should be an autonomous system. All the electricity consumed during the operation of the ship should be produced on board. In the case of the ship of this thesis, it is generated in a generator and in the solar panels. The only external aid that can have the ship are the in port electricity services, which are just used to charge batteries. The ship's electric power plant distributes all the energy produced to the consumers, using the main and the secondary switchboards. This consumers are all the services on board, and the electrical motors, in case that the ship has them.

The most typical form to represent a ship's electric power plant is using a one-line diagram. An one-line diagram is a simplified form to represent an electric installation. On it, there can be seen the electricity sources, the consumers and the way they are connected to each other. The figure 9.1 shows the one-line diagram of the ferry Côte d'Albâtre.



9.1: One-line diagram

Source: The author. (2018)

As it can be seen in the figure, there are five electrical energy sources. The first one is the port connection, which is going to be used while the ship is moored to cover the full electric power demand during the stay in port. There are three electrical generators capable to produce a power of 2x1.100 kW each one. These three generators are helped in their task of producing electricity by the solar panels installed on the top of the ship.

9.1- Layout of solar modules location on the ship

The first stage to do an installation of solar cells is to know which is the available surface for their installation. In the case of the ferry Côte d'Albâtre, the solar panels will be installed below the upper deck of it. As it is stated before in this thesis, ro-pax ferries are suitable for having photovoltaic installations because they have an unused upper deck, which is not needed for the charge of discharge of them. In another type of carrier, the main deck is used in this operation. This is the example of bulk carriers. In the case of ro-ro ships, the charge and the discharge are made by the side of the ship.

In the case of the ferry Côte d'Albâtre, there are two free surfaces in the upper deck for the installation of the photovoltaic panels. These two fields are separated by the chimney in where the exhaust gases of the engines are expelled to the atmosphere.The total surface for solar panels has been calculated using the following expression:

$$S = B\,(L' + L'')$$

Where: S means total surface

B means beam of the ship

L' means length of the first location of solar panels

L" means length of the second location of solar panels

The first location of solar panels has a length of 64,77 m, the second one has a length of 25,15 m. In both areas, the beam is the ferry's one, 24,2 m. With this data, the total surface in where install the photovoltaic modules is 2176,06 m^2.

There have been compared two commercial solar modules. Both solar panels are distributed by the same company: SolarLand. The first one is a monocrystalline silicon solar cell panel. Its commercial name is SLP190S-24. It is able to offer a maximum power of 190 W with a radiation of 1000 W/m^2 and at a temperature of 25ºC. It is equipped with a high transparent low-iron tempered glass, in order to make it resistant to corrosion and wind pressure. Every module is 1580 mm large, 808 mm wide and 35 mm thick and has a weight of 19 kg. In the table 9.2 there are shown the electrical characteristics of the solar cell SLP190S-24.

Maximum power (Pmax)	190 W
Voltage at Pmax (Vmp)	36,8 V
Current at Pmax(Imp)	5,16 A
Open-circuit voltage (Voc)	45,0 V
Operating temperature	-40ºC to 85ºC
Power tolerance	± 5%

9.2: Electrical characteristics of SLP190S-24

Source: SolarLand. (2017)

As it can be seen in the table, every cell offers a maximum electric power of 190 W at a voltage of 36,8 V and a current of 5,16 A. The operating temperature of this type of solar cell is from -40ºC to +45ºC. This means that it can be used in the English channel, the region of operation of the ship Côte d'Albâtre.

According to the data provided by SolarLand, every module has a surface of 1,28 m^2. The ferry Côte d'Albâtre has a useful surface for solar panels of 2176,06 m^2. That means that there could be installed 1700 solar panels. Every solar panel has a price of $275,00. This would mean a total price of $467.500,00.

The second type of solar panels studied is SPR-E-Flex-100. It is a flexible solar panel distributed by the company SolarLand. It offers a nominal power of 100 W with a radiation of 1000 W/m^2 and at 25ºC. They can flex up to 30º without power loss and weight 2 kg. In the table 9.3 there can be seen the electrical data of this flexible solar panels.

Nominal Power (Pnom)	100 W
Rated Voltage (Vmpp)	17,1 V
Rated Current (Impp)	5,9 A
Open-circuit voltage (Voc)	21,4 V
Short-circuit current (Isc)	6,3 A
Power Temp Coefficient	-0,35 %/ºC
Voltage Temp Coefficient	-58,9 mV/ºC
Current Temp Coefficient	2,6 mA/ºC
Maximum voltage	45 V

9.3: Electrical characteristics of SPR-E-Flex-100

Source: SolarLand. (2017)

As it can be seen above, the nominal power of every cell is 100 W at 17,1 V and 5,9 A. This characteristics have been calculated at a temperature of 25ºC. As it is explained in the chapter 5 of this thesis, when the temperature of the solar cell increases, its efficiency decreases. In the case of SPR-E-Flex-100, there is a loss of 0,35% of the power offered for every degree of temperature increased. This provokes a loss of 58,9 mV and a gain of 2,6 mA, for every degree.

As stated in the information provided by SolarLand, every panel is 1165 mm large, 556 mm wide and 20 mm thick. This dimensions represent a surface of 0,65 m^2. With an effective surface of 2176,06 m^2 for the installation of solar panels, there can be installed 3347 flexible panels. Every solar panel has a price of $253,00, that would mean a price of $846.791,00.

To choose which solar panels are the best option to be installed in the ship, it is necessary to calculate the electrical energy produced by every panel if it was installed in the ferry Côte d'Albâtre. In the next table there can be seen the total energy produced by every solar panel. In the left side there is the calculation of the energy for the flexible solar cell, and in the right side there is the calculation of the energy of the monocrystalline cell, considering that the ship spends half a year in every port. As it is stated in the table below, monocrystalline cells produce more energy than the flexible ones, with the same surface of operation. Moreover, the purchase of the monocrystalline panels is cheaper than the acquisition of the flexible ones. According to this reasons, the solar panels used in this thesis are the monocrystalline cells distributed by SolarLand with the commercial name of SLP190S-24.

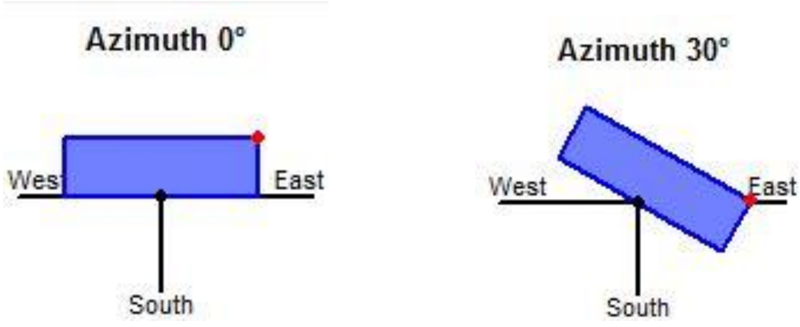
Specification	Portsmouth	Le Havre
Power demand (kW)	2914,29	
Useful surface for panels (m2)	2176,06	
Surface of every solar panel (m2)	0,65	
Number of solar panels	3347	
Power of 1 solar panel (kW) at 1000W/m2	0,10	
Radiation (kWh/m2)	950,00	1100,00
Hours of solar radiation	800,00	808,50
Energy of one solar panel (kWh)	52,00	52,55
Energy of all solar panels (MWh)	174,04	175,89
Flexible solar cells		

Specification	Portsmouth	Le Havre
Power demand (kW)	2914,29	
Useful surface for panels (m2)	2176,06	
Surface of every solar panel (m2)	1,28	
Number of solar panels	1700	
Power of 1 solar panel (kW) at 1000W/m2	0,19	
Radiation (kWh/m2)	950,00	1100,00
Hours of solar radiation	800,00	808,50
Energy of one solar panel (kWh)	194,56	196,63
Energy of all solar panels (MWh)	330,75	334,27
Monocrystalline solar cells		

9.4: Comparison between monocrystalline and flexible solar panels.

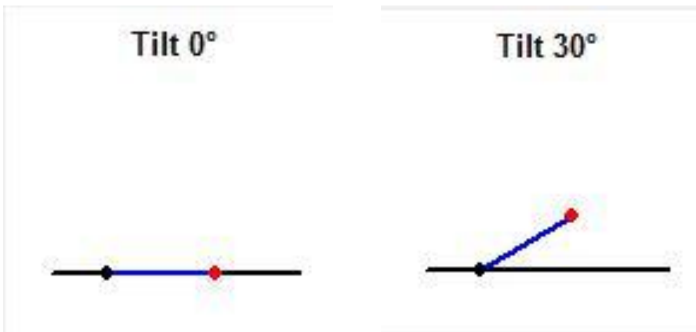
Source: The author. (2018)

The most common way to install solar panels is to install them with a certain inclination in order to maximize their efficiency. In an inland installation, there would be a study of the panel's position regarding the direction of maximum solar radiation. The photovoltaic module would be installed facing the south, if it is installed in the north hemisphere, and facing the north if it is installed in the south hemisphere. The angle between the solar panel and the meridian in where it is placed is called Azimuth. In the figure 9.5 there can be seen two examples of a solar panel location with different value of the Azimuth angle.



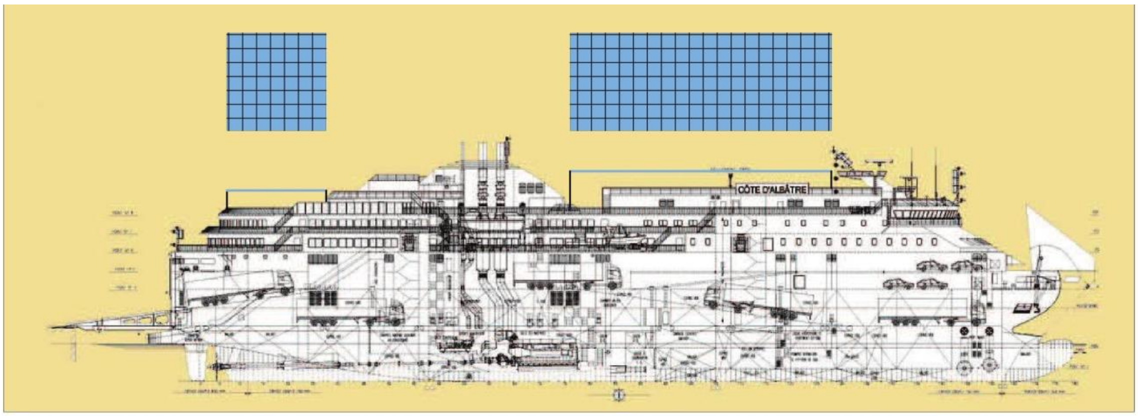
9.5: Examples of different Azimuth angle.
Source: PVsyst V6.72. (2018)

The other parameter that has to be considered in an inland installation, is the inclination of the solar panels. This inclination angle is called Tilt. Depending on the exact location on the planet, the solar panels need more or less Tilt. Due to the fact that the sun's rays do not have the same inclination in every zone of the Earth, the solar panels need to have a different inclination for each zone in order to take the major advantage of the sun radiation. The position of the solar panels depends also on the horizon of their location. They are installed in order to take the major advantage of the solar radiation concerning all the shadows of the elements located close to the solar panel.



9.6: Examples of different Tilt angle.
Source: PVsyst V6.72. (2018)

The case of an installation of solar panels in a ship is quite different that an inland installation. A ship is continuously moving during its normal operation. Due to this, the Azimuth angle is changing with the movement of the ship. By cause of this, there is no sense in giving to the solar panels any inclination angle. If it was done, the solar panels would not receive solar radiation depending on the ship's location. In the figure 9.7, there is showed the layout of the solar modules location on the ferry Côte d'Albâtre.



9.7: Layout of solar modules location on the ferry Côte d'Albâtre.
Source: The author. (2018)

As it is showed in the figure above, there are two fields of solar panels. They are located in the upper deck of the ship. The biggest one is located between the navigation bridge and the exhaust gas chimney. It has a surface of 1.567,43 m^2. The second field, located in the stern of the chimney, has a surface of 608,63 m^2.

10- DETERMINATION OF THE AMOUNT OF FUEL SAVED

In a ship, the generation of electrical energy is made using an electric generator. In this project, the electricity sources of the ship are the generator, fed with fuel-oil, and the photovoltaic modules installed in the upper deck. As a result of the installation of the solar modules, there is a fuel saving, as the power demand of the generator is lower than if it had to produce all the electrical energy. To determinate the amount of fuel saved, it is necessary to determinate the electrical power generated by the solar panels. As it is calculated in the chapter 9, the solar panels produce, considering that the ship spends half a year in Portsmouth and the other half of the year in Le Havre, 330,75 MWh when the ship is located in Portsmouth, and 334,27 MWh when it is located in Le Havre.

The average annual hours of solar radiation are 1.600 in Portsmouth and 1.617 in Le Havre. According to this, there have been estimated the average annual hours of solar radiation in the part of the English channel between both cities. The result of this is 1.608,5 annual hours of solar radiation. The timetable of the ferry Côte d'Albâtre has been consulted to the travel agency Direct Ferries. As it is stated, every day the ship spends 8,5 hours in Le Havre, 6,5 hours in Portsmouth, and 9 hours sailing from one port to the other. As a year has 8.760 hours, the ship is receiving solar radiation the 18% of its operation time.

There have been calculated the energy produced by the solar panels in every location after one year of operation of the ship.In the table 10.1 it can be seen the synopsis of the calculation of the total energy produced by the photovoltaic cells.

	Specifications		Portsmouth	Le Havre	Cruising
[1]	Power demand (kW)		2.914,29		
[2]	Useful surface for panels (m2)		2.176,06		
[3]	Surface of every solar panel (m2)		1,28		
[4]	Number of solar panels		1.700		
[5]	Power of 1 solar panel (kW) at 1000W/m2		0,19		
[6]	Radiation (kWh/m2)		950,00	1.100,00	1.025,00
[7]	Annual hours of solar radiation		1.600,00	1.617,00	1.608,50
[8]	Percentage of annual hours of solar radiation	[7]/8.760	0,18	0,18	0,18
[9]	Daily hours spent by the ship in the location		6,50	8,50	9,00
[10]	Annual hours of radiation received by the ship	[8]x[9]x365	433,33	572,69	603,19
[11]	Energy of one solar panel (kWh)	[3]x[5]x[10]	105,39	139,28	146,70
[12]	Energy of all solar panels (kWh)	[4]x[11]	179.157,33	236.771,92	249.381,84

10.1: Summary of the calculation of the energy produced by the solar panels.

Source: The author. (2018)

The energy produced by one solar panel is calculated using the following expression:

$$E = S \cdot P_i \cdot t$$

Where: E means energy produced by one solar panel, in kWh

S means the surface of one solar panel, in m^2

P_i means the power that produces one solar panel, in kW/m^2

t means the time of solar radiation, in h

The energy produced by all the solar panels is the energy produced by one solar panel multiplied by the total number of solar panels. As there are 2176,06 m^2 available for the location of solar panels, and every panel has a surface of 1,28 m^2, there can be located in Côte d'Albâtre's roof 1700 solar panels. After one year of operation of the ship, the energy produced by the solar panels is: 179,16 MWh, in the time spent in Portsmouth, 236,77 MWh, in Le Havre and 249,38 MWhwhile sailing between the two ports.During the sailing time between both cities, there have been considered the hours that Côte d'Albâtre needs to sail from one port to the other. The distance between Portsmouth and Le Havre is 96,65 nm, considering the service speed of the ferry, 22 knots, the time journey time is 4 hours and 24 minutes. Using the expression above, in this time the solar panels are able to produce 1,07 kWh.

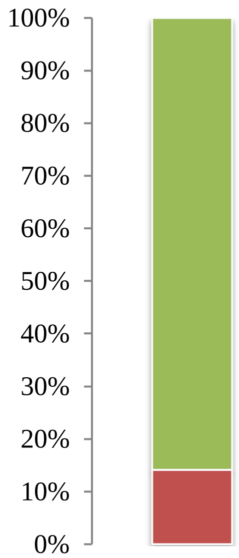
The meteorological data from Portsmouth has been obtained from Med Office, the meteorological office of the United Kingdom, the data from Le Havre has been obtained from Météo France, the same institution in France. As it can be seen in the table 10.1, the annual average irradiation in Portsmouth is 950 kWh/m^2, while in Le Havre is 1100 kWh/m^2. The average annual hours of solar radiation in Portsmouth are 1600, while in Le Havre are 1617.

	Specifications		Portsmouth	Le Havre	Cruising
[1]	Power demand (kW)		2.914,29		
[2]	Useful surface for panels (m2)		2.176,06		
[3]	Surface of every solar panel (m2)		1,28		
[4]	Number of solar panels		1.700		
[5]	Power of 1 solar panel (kW) at 1000W/m2		0,19		
[6]	Radiation (kWh/m2)		950,00	1.100,00	1.025,00
[7]	Annual hours of solar radiation		1.600,00	1.617,00	1.608,50
[8]	Percentage of annual hours of solar radiation	[7]/8.760	0,18	0,18	0,18
[9]	Daily hours spent by the ship in the location		6,50	8,50	9,00
[10]	Annual hours of radiation received by the ship	[8]x[9]x365	433,33	572,69	603,19
[11]	Energy of one solar panel (kWh)	[3]x[5]x[10]	105,39	139,28	146,70
[12]	Energy of all solar panels (kWh)	[4]x[11]	179.157,33	236.771,92	249.381,84
[13]	Power generated by solar panels (kW)	[12]/[10]	413,44	413,44	413,44
[14]	Covering of the power demand (%)	100x[13]/[1]	14,19	14,19	14,19
[15]	Specific fuel consumption (kg/kWh)		0,19		
[16]	Fuel saving (kg/h)	[13]x[15]	78,68	78,68	78,68
[17]	Fuel price ($/kg)		0,53		
[18]	Money saved ($/h)	[16]x[17]	41,70	41,70	41,70
[19]	Money saved every year ($)	[10]x[18]	18.069,63	23.880,58	25.152,40
[20]	Total money saved every year ($)		67.102,61		

10.2: Amount of fuel and money saved according to the price given by Rotterdam Bunker Prices.

Source: The author. (2018)

As it is showed in the table 10.2, the electrical power generated by the solar panels is the 14,19% of the total power demand in the most adverse condition of operation: Manoeuvre. As the electric balance of the ship says, in this condition, the power demand is 2.914,29 kW. The power generated by the solar panels is the total energy that they produce divided by the hours that they need to produce it. In the case of the other operating conditions, the percentage of the power demand covered by the solar panels is higher.



10.3: Percentage of the power demand covered by the solar panels.

Source: The author. (2018)

As a result of this electrical power generated by the solar panels, there is a saving of fuel. The electrical generators installed on board need to produce the 85,81% of the power demand, in the manoeuvre condition. This amount of energy corresponds to the green zone of the graph 10.3.

This reduction of the power demand of the electrical generators, supposes the saving of 78,68 kg/h of fuel.

The calculation of the amount of fuel saved has been made using the data provided by the generators producer, Wärtsilä. As it is stated in the chapter 6 of the thesis, the ferry Côte d'Albâtre has three Wärtsilä electric generators that offer a power of 2x1.100 kW each one. As it can be seen in the table 10.2, the fuel consumption of every electric generator is 0,1903 kg/kWh.The fuel saved is its consumption times the power generated by the solar panels. This fuel saving involves a money saving during the operation of the ship. To calculate the amount of this money saving, it is necessary to know the price of the marine fuel oil. The ferry Côte d'Albâtre operates in the English channel, between France and the United Kingdom. This region of the Earth is an ECA. ECAs are special regions of the planet in where the maximum SO_X and NO_X emissions are more restricted than in the other territories, as it is explained in the chapter 3 of this thesis. According to this, the fuel-oil used in Côte d'Albâtre is called Low Sulphur Fuel Oil. This type of fuel permits to respect the maximum emissions accorded in the MARPOL convention.

The price of the fuel oil is a value that fluctuates every day. Depending on the geopolitics and the relations of countries, the petrol price fluctuates. This provokes a constant variation of the fuel price. The fuel price depends also on the port in where it is bought. Every country has its own taxes for fuel. Due to this, the price of the fuel consulted is the price in the port of Rotterdam. The port of Rotterdam offers the price of the fuel on real time on its webpage. When the consult of the price was made, the 12th of June of 2018, the price of the Low Sulphur Fuel Oil was 613,00 $/mt. As the calculation of the amount of fuel saved is done in terms of mass, this price has been conversed to $/kg. The conversion has been made using the same fuel density above, 0,945 kg/l.

As it can be seen in the table 10.2, the amount of money saved every hour thanks to the use of the solar panels is 41,70 $/h. This saving of money occurs only during the time when the ship is receiving solar radiation. As it is stated in the table 10.2, in one year of operation, the ferry saves $18.069,63 in the time being in Portsmouth, $23.880,58 while it is in Le Havre, and $25.152,40 cruising. This places an annual saving of money of $67.102,61. As the price of all the solar panels was $467.500,00, the initial investment is regained after 7,5 years.

11- CONCLUSIONS

As it is known, maritime transport is the more efficient mean of transport, concerning the pollution by unit of load. However, in absolute terms, the maritime transport of people or goods is a great pollutant of the atmosphere and of the maritime environment. The fuel used in ships is less refined than the used in the other means of transport. Therefore, it emits more sulphur and nitrogen oxides.

The aim of this thesis was to reduce the pollutant emissions of a ro-pax ferry, reducing its consumption of fuel-oil. This consumption reduction would also induce a money saving by the operator of the ship, in terms of the saving if fuel-oil. Another objective of the work was to discern the extend of the application of the solar energy in large ships. Large ships have a high electric power demand, and the power that can be offered by the solar panels is not enough to supply all the demand.

As it is proved in this thesis, solar energy can be used as a secondary energy source, in order to sustain the ship's power plant. Solar energy can be very useful in small boats, but in large ships with a huge energy demand, it cannot be considered as the only electrical energy source. Considering large ships, ro-ro are appropriated to host solar panels, as they have a huge and free upper deck in where to place them. This is not possible in container ships. In the situation studied in this thesis, photovoltaic modules are able to produce the 14,19% of the electrical power demand of the ferry Côte d'Albâtre.

According to this, solar energy can be considered as a valid source of electrical energy, if it is contemplated as a secondary source, as it is said. Economically, the installation of the solar panels results profitable. As it is stated in the last chapter of the thesis, an eventual installation of 1.700 solar panels would be profitable after two years of operation of the ship.

A logical solution would be to combine solar energy with other renewable energies, in order to contribute more to the ship's solar plant. Hybrid solutions like the wind and solar use simultaneously, can be more useful. As it is explained in the thesis, nowadays there exist ships that use both energies at the same time. This is the case of Sydney Solar Sailor, which uses rigid sails equipped with solar panels. Another coherent solution would be to use the solar energy in an other way. Solar energy can also be used as heat energy. Solar energy can be part of the steam system on board as a water heater.

Even though renewable energy sources are starting to become enough significant to be used on ships, nowadays there are not any regulations about the use of solar energy on board. The existence of any international convention or regulation in that regard would help to the implementation of the solar energy into the shipping industry.

Another obstacle of the solar energy is that it is conditioned by the weather conditions -as all renewable energy sources. Solar energy can only be used during the hours of solar radiation, letting the ship without any electrical energy production during night hours. In the case of solar energy, the location of the ship has a lot of importance too. The percentage of energy provided by the solar panels changes depending on the radiation that they are receiving from the sun. As a result of this, the ship's power plant is adjusted to the energy provided from the solar panels.

Given the above, solar energy is not a great electrical energy for ships, it should be considered as a way to reduce the pollutant emissions of it, and as a way to reduce the cost of operation of the ship. With the international organisations putting more attention on the protection of the marine environment, renewable energy sources will be considered as a suitable solution for ships in the nearby future. Therefore, new ship designers will have to pay attention to renewable energy sources, and make them even more effective in the future.

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ZACHODNIOPOMORSKI UNIWERSYTET TECHNOLOGICZNY W SZCZECINIE

WYDZIAŁ TECHNIKI MORSKIEJ I TRANSPORTU

ANNEX I: Specification sheet of the solar panels

Oriol Carrasco Serra

The possibility of solar energy use on ro-pax ferries

Thesis director,

Wojciech Zeńczak ph D, D.Sc

Assistant professor

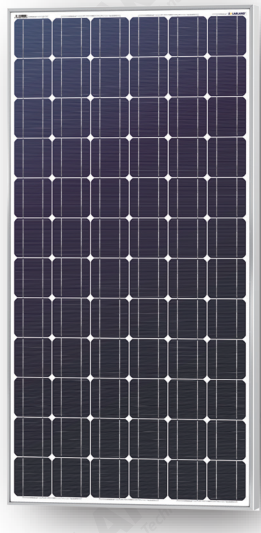
Szczecin, 2018

SLP190S-24

High Efficiency Monocrystalline PV Module

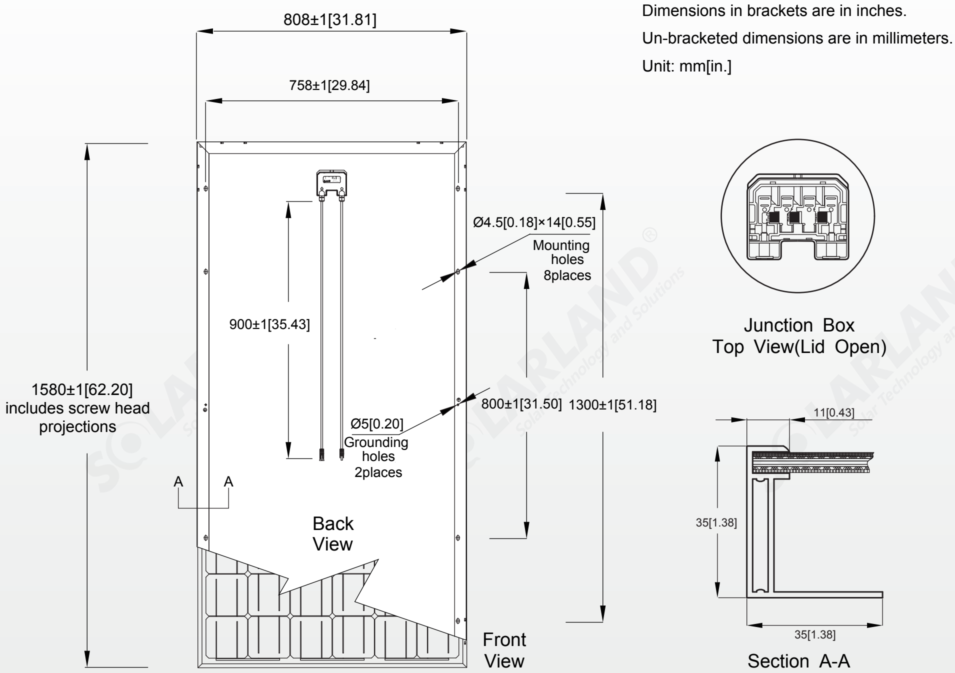
Electrical Characteristics	SLP190S-24
Product code	190022401D
Maximum power (Pmax)	190W
Voltage at Pmax (Vmp)	36.8V
Current at Pmax (Imp)	5.16A
Open-circuit voltage (Voc)	45.0V
Short-circuit current (Isc)	5.56A
Temperature coefficient of Voc	-(80±10)mV/°C
Temperature coefficient of Isc	(0.065±0.015)%/ °C
Temperature coefficient of power	-(0.5±0.05)%/ °C
NOCT (Air 20°C; Sun 0.8kW/m² wind 1m/s)	47±2°C
Operating temperature	-40°C to 85°C
Maximum system voltage	1000V DC
Power tolerance	± 5%

*STC: Irradiance 1000W/m², AM1.5 spectrum, module temperature 25°C
*NOCT:Nominal operating cell temperature (the data is only for reference)



Module Diagram

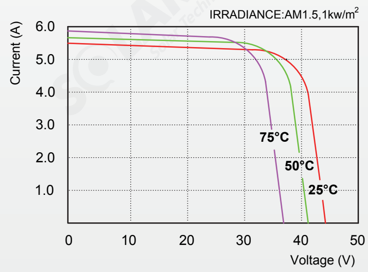
Dimensions in brackets are in inches.
Un-bracketed dimensions are in millimeters.
Unit: mm[in.]



Features

- Nominal 24V DC for standard output.
- Outstanding low-light performance.
- Heavy-duty anodized frames.
- High transparent low-iron,tempered glass.
- Rugged design to withstand high wind pressure, hail and snow load.
- Aesthetic appearance.

Characteristics



SLP190S-24 I-V Curves

Specifications	SLP190S-24
Cells	Monocrystalline silicon solar cell
No. of cells and connections	72(6X12)
Module dimension	1580mm[62.20in.]x808mm[31.81in.]x35mm[1.38in.]
Weight	19kg[41.89lbs]
Packing information(Carton)	1625mm[63.98in.]x855mm[33.66in.]x70mm[2.76in.]/(1pcs/ctn)

*Limited warranty: 2-year limited warranty of materials and workmanship; 10-year limited warranty of 90% power output; 25-year limited warranty of 80% power output.For detail, please contact us.
*Specifications are subject to change without notice at any time.