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Renewable energy production in the Port of Santander, Spain

– A case study

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Abstract

This project work will focus on the renewable energy production in the Port of Santander, a city located in the northern coast of Spain. Since the last year, the Port Authority of Santander has been considering the possibility of constructing a renewable energy power plant in order to satisfy the increasing energy demand in the port. For this reason, three alternative renewable energy sources will be studied in this project: solar energy, wind energy and marine power (tidal power and wave power). The project will cover a theoretical study of each of the energy sources, clarifying its advantages and disadvantages, as well as the current state of development of each technology and which parameters make a certain location suitable for the installation of a power plant of each type. Afterwards, there will be a presentation of the data gathered. This data will correspond to the parameters studied in the theoretical section. Afterwards, all the information obtained will be discussed and compared between the different alternatives in order to choose one of them, summarizing in the conclusion section all the reasons why this option was chosen above the others. After analyzing all the data and compare it between the different alternatives, it is concluded that wind energy has the highest possible capacity occupying less area. Also, it can be located in areas that do not interfere with the port normal activity and without occupying useful area on land by building an offshore wind farm.

Acknowledgment

This final thesis work presented aims to find which renewable energy source is the most suitable alternative for the energy production in the port of my home city, Santander. All of the data gathered has been obtained thanks to the Port Authority of Santander and the Ports of Spain. This project work has been written as a requisite for obtaining the Bachelor Degree in Industrial Engineering during the period between February and May of 2020.

First of all, I would like to thank Mariana Andrei for accepting being my supervisor even as an Erasmus student, with all the difficulties that this could cause; and for her guidance during the first weeks of the project - when I did not even know how to structure it - and throughout the next months until now.

The project emerged in a casual conversation with my father, Antonio, during an evening walk in Santander's city centre talking about his job at the port. I would not have been able to gather most of the data in this project without his help, that is why I want to specially thank him. Of course, I also want to thank all my family for the support they have given me during this months away from home, which turned out to be harder than originally expected, your advice during these months has been, as always, the greatest pillar I could find. You have always given me back the motivation whenever I lost it. Finally, I want to thank my friends, the ones I made during these months and the ones I have in Spain (some of them now scattered around Europe) for also supporting me and offering their help, even if that consisted in insisting me to keep writing. To all of you, and the ones who I am surely missing:

Thank you.

I hope you enjoy the reading.
Pablo Cortiguera Ruiz.

Linköping, May 20^{th} 2020.

Contents

To everyone that supported me, you know who you are.

1. Introduction

Since the beginning of the human race, energy has been one of the main causes of its evolution up to the present day situation. The most primitive form of energy used by humans was fire. Such is the importance of fire, that it is considered as a property of intelligence that differentiates humans from the rest of the animals, being able to manipulate it and use it for cooking or even manufacturing tools and weapons later in history. The use of fire dates back 400,000 years ago [1], when humans lived in caves and lit fires to heat the place, cook the food, have light for night activities and protection against animals and insects. On the whole, the control of fire by early humans is considered the beginning of human development for the next thousands of years until today. But, nowadays, we do not use fire anymore.

Fire was one of the main, and the most important, ways of energy production for the next thousands of years, along with, for example, early uses of hydro power in watermills. It was not until the Industrial Revolution in the 18^{th} century that energy was used in more sophisticated ways than just using fires for heating and lighting. With the commercialization of the steam engine in 1712, the use of fire evolved and started being used as a way of powering the steam engine by burning materials (mainly coal). From then until our days, energy has been used in several ways and forms, from electricity to combustion engines. But, now, another problem arises.

During all this time, the energy production has been made by burning material. In the first place, wood was used for lighting fire, however, with the increase of population and energy needs, other sources such as coal and oil were introduced for burning, as they were more efficient than wood and the forests were being deforested. As seen in figure 1.1, in the 20^{th} century the use of coal and, later, oil increased to the point of being more important than traditional sources like wood. The problem of all these energy sources (which include natural gas later in the 21^{st} century), is that all of them produce greenhouse gases when they are burnt. Because of this, the amount of greenhouse gases in the atmosphere is one of the main causes that are producing the problem that humanity is facing nowadays: climate change.

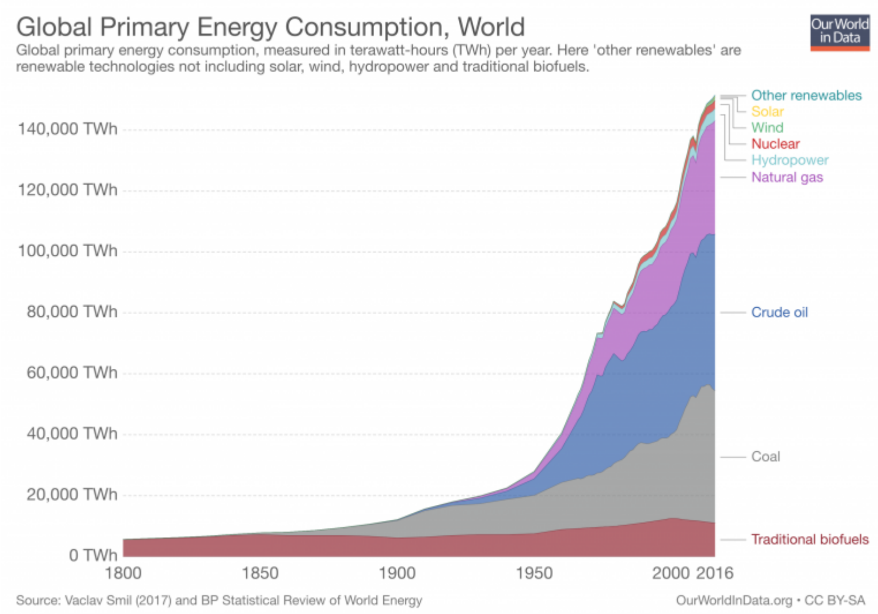


Figure 1.1: Global use of energy sources since 1800. Source: Our World in Data [2].

For the last decades, the concentration of CO_2 in the atmosphere has been increasing steadily. Looking at figure 1.2, the total emissions of carbon dioxide in 2015 exceeded 35 billion tons. In response to the increasing emissions of greenhouse gases, alternative renewable energy sources have been investigated and developed for the last decades. A renewable energy is 'energy produced from sources that do not deplete or can be replenished within a human's life time' [3]. Coal, oil and natural gas resources are limited, and the process in which they are produced lasts for thousands of years; but, on the other hand, renewable energy sources are inexhaustible: wind, sunlight, water in motion... The other advantage that renewable sources have is that they do not produce greenhouse gases emissions, as they do not require the burning of any material. Since the investigation of these alternative energy sources began, many governments have encouraged their use and promoted their implementation into the electric mix financing their construction. For example, Denmark has one of the highest energy taxes for the carbon dioxide produced in Europe but, this way, they promote the energy production via renewable sources. Along with Denmark, many of the European countries, and many other around the world, started investing in renewable sources in order to decrease their greenhouse gasses emissions. Figure 1.3 shows how the annual CO_2 emissions contribution in these countries have been reduced significantly within the last years. However, other countries, such as China, have increased their contribution and, looking again at figure 1.2, it is notable that, although some countries reduce their contribution, the total amount of CO_2 emitted to the atmosphere is still increasing.

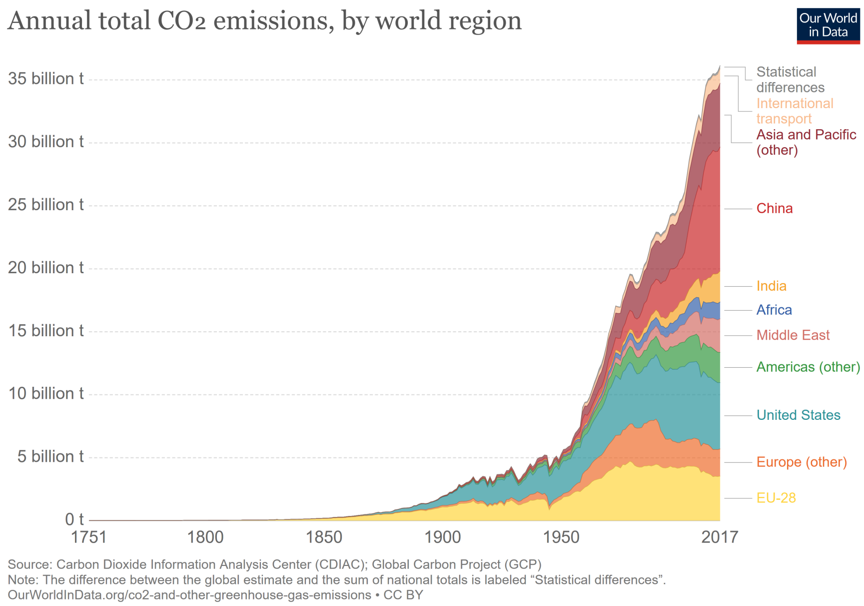


Figure 1.2: Global CO_2 emissions by region. Source: Our World in Data [4].

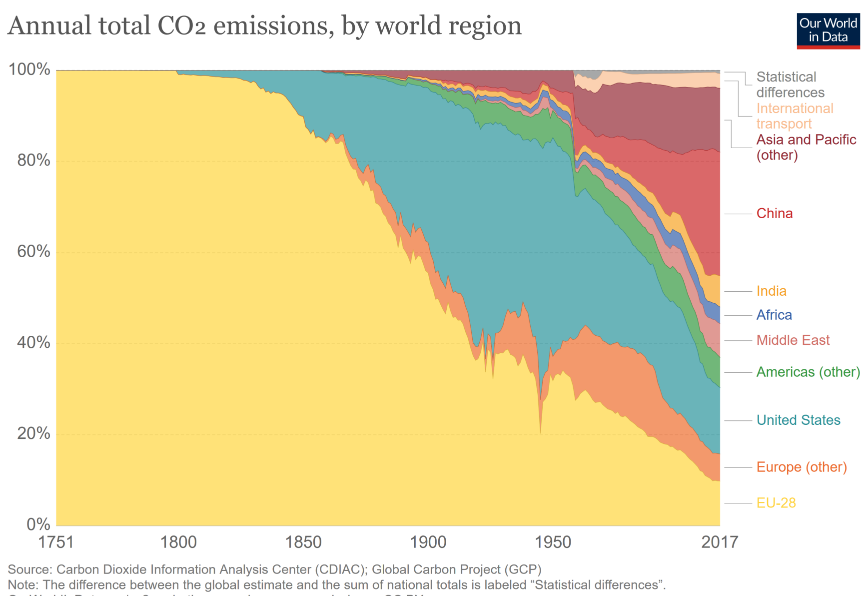


Figure 1.3: Relative global CO_2 emissions by region. Source: Our World in Data [4].

Because of these facts, it is notable that there is still a long way to go if it is intended to reach the global goal of reducing greenhouse gas emissions in order to 'hold the global temperature increase below 2ºC above pre-industrial levels' as said by the UN in the Paris Agreement from 2016 [5].

More specifically, Spain has developed a similar policy regarding renewable energy sources since the end of the 20^{th} century. The main renewable energy source during that century was hydraulic power but, during the last decades, it has been supplemented with other renewable energies such as solar power, wind power and thermal energy, along with carbon-free nuclear energy. So that, Spain produced in 2019 85.6% less energy from coal-fired thermal plants than in 2002 [6]. This reduction does not mean that the overall energy production has decreased since 2002, but that the amount of energy produced by natural gas burning and renewable energy sources has increased year by year.

European governments agreed to increase their renewable energy shared consumption to 20% in 2020, but most of the countries - Spain included - have not fulfilled these objectives [7]. In the best of the scenarios, Spain would get only 12.6% - 17.1% instead of the forecasted 20.8% [7]. Looking at the energy demand, due to the economic crisis in 2008, energy consumption in Spain decreased as a result of the closure of many industries in the country as seen in figure 1.4, changing the increasing demand tendency from the previous years.

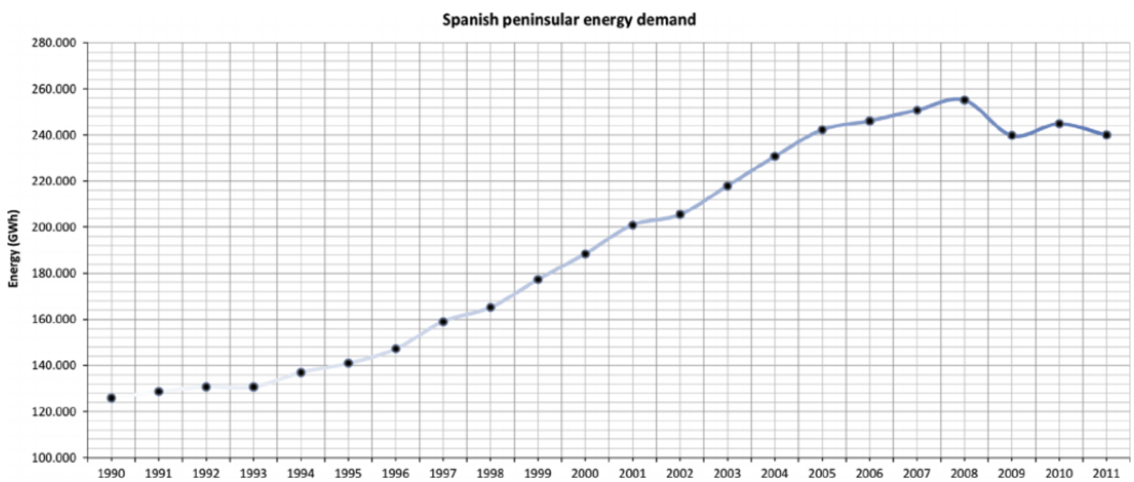


Figure 1.4: Energy consumption per year in Spain (mainland). Source: Eurostat [7].

As for the renewable energies situation in Spain, the country has a great potential in terms of domestic renewable energy production. The total amount of energy that could be produced using renewable energies is larger than the amount produced by fossil fuels nowadays, and even greater than the Spanish energy demand. This means that, if this potential is exploited, Spain could become an energy-exporter country instead of importer as it is currently. Sorting out the most important renewable energy sources, solar energy would be the first, followed by wind power, hydroelectric, wave and geothermal energy. As it was said before, hydroelectric power was the first green energy source to be exploited in Spain and, by now, it has developed almost to its peak of potential. This means that the remaining options for new hydroelectric plants are a few and with a lower capacity.

Instead, solar energy has a large potential among most of the territory in Spain. According to figure 1.5, the southern part of the Spanish territory, as well as the Canary and Balearic Islands, have a high photovoltaic power potential. Northern Spain has a lower potential although, depending on the region, it gets also a substantial amount of sun radiation during the whole year (observe the regions around Zaragoza). Approximately, the northern regions of Spain receive around 1600 h of sunlight per year while the southern regions get as much as 3100 h. Also, the average solar radiation for the country is 1600 kWh/m^2 [8]. The new energy regulations in 2007, combined with these factors, allowed the Spanish solar energy installed capacity to increase greatly between 2007 and 2009 (see figure 1.6). For these reasons, Spain ranked in the top places of countries with the most installed capacity of solar photovoltaics during the first years of evolution of this technology. For the last years, this sector experienced a crisis in Spain because of legal concerns, such as the elimination of the incentives to the solar energy, which prevented the country to keep ranking as a top country in photovoltaics.

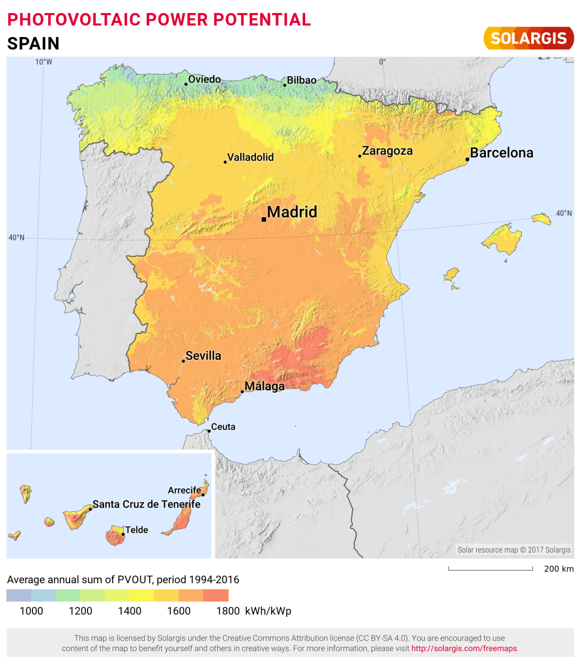


Figure 1.5: Photovoltaic power potential in Spain. © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

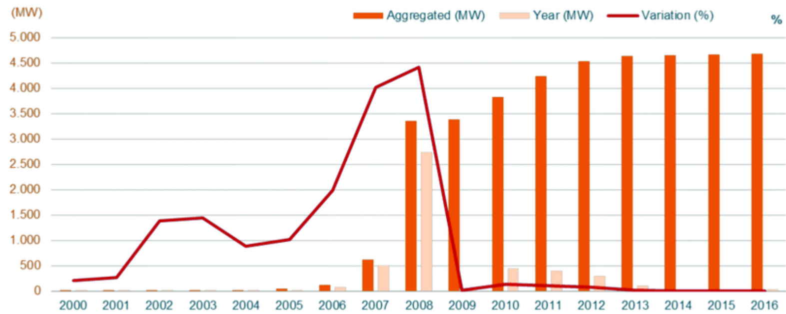


Figure 1.6: Photovoltaic solar installed capacity in Spain, 2000-2017. Source: Sustainability [9].

As for other renewable energy sources, Spain has also been leader in terms of wind energy. This type of renewable energy has been in constant increase (figure 1.7) since the beginning of the 21^{st} century until today, becoming the most important renewable energy in the country and generating almost 18% of the total national annual energy demand. As it happens with the solar energy, wind energy in Spain is concentrated in the regions with the strongest winds, mostly in the center of the country (Castilla y León and Castilla la Mancha) and along the north-west and south coasts in Galicia and Andalucía as seen in figure 1.8. The legal concerns mentioned for solar energy have affected also wind energy, slowing its development in the recent years.

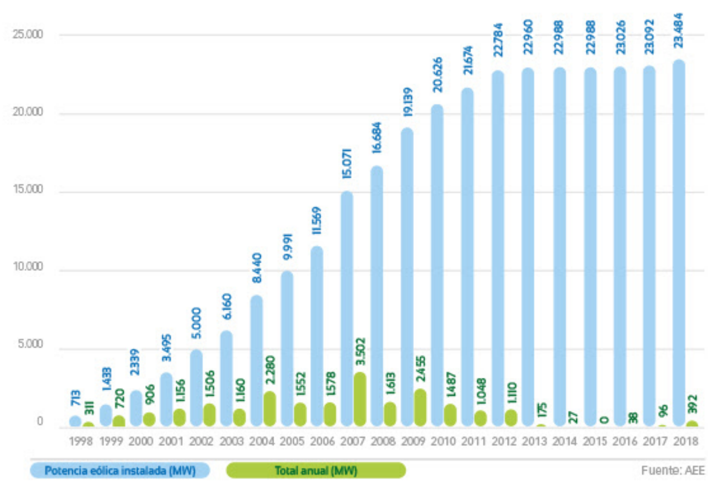


Figure 1.7: Annual and cumulative evolution of the installed wind power in Spain (1998-2018). Source: Reve [10].

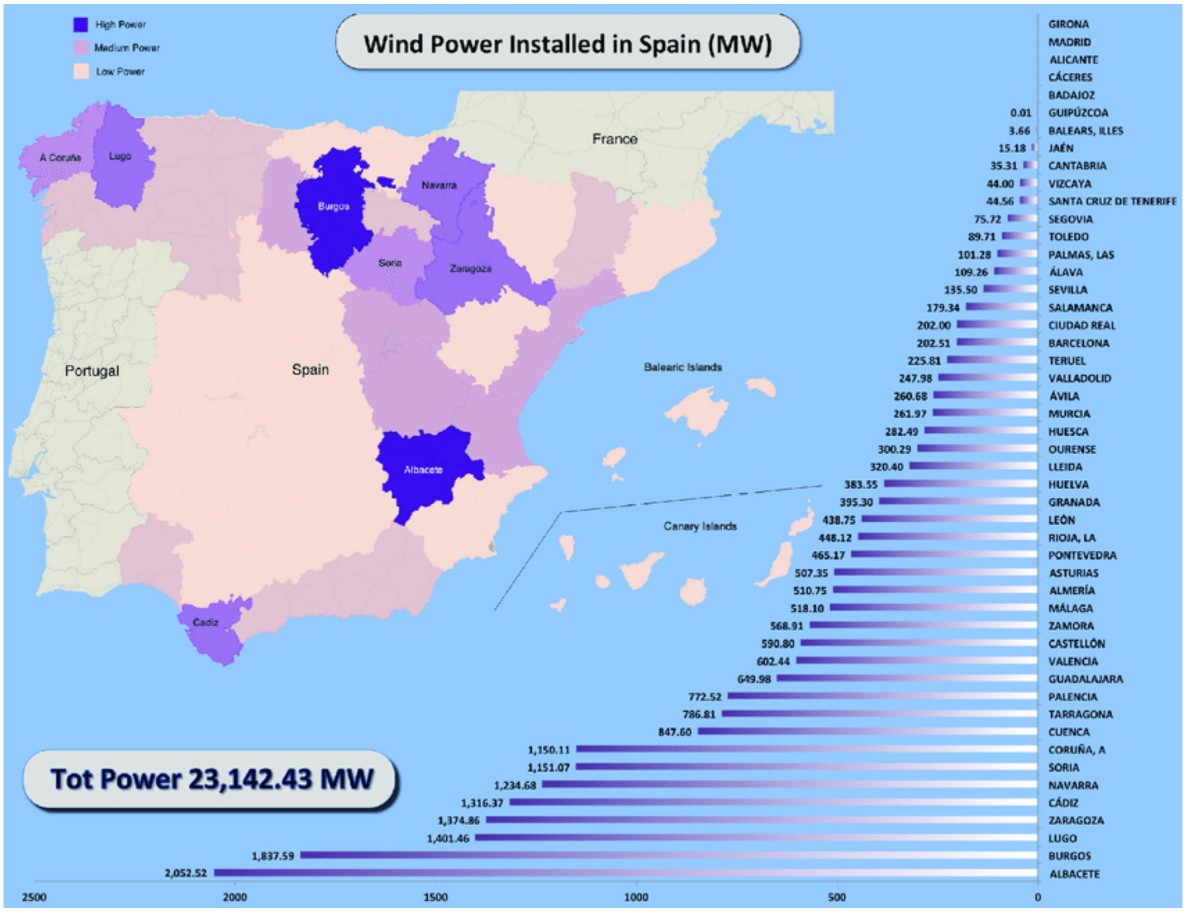


Figure 1.8: Location of the wind power production in Spain by province. Source: Renewable and Sustainable Energy Reviews [7].

Besides, hydroelectric power is, as stated before, the first renewable energy used at a large scale in Spain due to the country's orography, which allowed the construction of multiple dams in the several mountain ranges over the territory. Because of these characteristics, Spain is the third country within the EU in terms of hydro power capacity (figure 1.9) and the sixth in terms of gross electricity production (figure 1.10). It is appreciated in figure 1.10 that the production decreased from 2016 to 2017. The cause of this decrease is that Spain is experiencing severe droughts in the last summers, so the water stored in reservoirs is used for other purposes rather than energy production.

	2016				2017			
	Pure hydro power	Mixed hydro power	Pumped hydro power	Total	Pure hydro power	Mixed hydro power	Pumped hydro power	Total
France	18 487	5 407	1 728	25 621	18 560	5 418	1 728	25 706
Italy	14 991	3 325	3 982	22 298	15 109	3 377	3 940	22 426
Spain	14 053	2 690	3 337	20 080	14 052	2 690	3 337	20 079
Sweden	16 367	99		16 466	16 403	99		16 502
Austria	8 493	5 623		14 116	8 506	5 644		14 150
Germany	4 573	1 187	5 540	11 300	4 449	1 178	5 493	11 120
Portugal	4 458	2 502		6 960	4 462	2 764		7 226
Romania	6 377	265	92	6 734	6 328	272	92	6 692
United Kingdom	1 835	300	2 444	4 579	1 874	300	2 444	4 618
Greece	2 693	699		3 392	2 693	699		3 392
Bulgaria	2 210	149	864	3 223	2 359	149	864	3 372
Finland	3 250			3 250	3 272			3 272
Slovakia	1 608		916	2 524	1 607		916	2 523
Poland	596	376	1 413	2 385	591	376	1 423	2 390
Czechia	1 090		1 172	2 262	1 093		1 172	2 265
Croatia	1 912	293		2 205	1 913	293		2 206
Latvia	1 564			1 564	1 564			1 564
Belgium	115		1310	1 425	113		1 310	1 423
Slovenia	1 113		180	1 293	1 167		180	1 347
Luxembourg	34		1296	1 330	35		1 296	1 331
Lithuania	117		760	877	117		760	877
Ireland	237		292	529	237		292	529
Hungary	57			57	57			57
Netherlands	37			37	37			37
Denmark	9			9	9			9
Estonia	6			6	7			7
Total EU 28	106 283	22 915	25 326	154 523	106 613	23 260	25 247	155 119

* Net maximum electrical capacity. Source: Eurostat

Figure 1.9: Net capacity of all hydro power plants by country. Source: Eurostat [11].

	2016	2017
Sweden	62.018	65.066
France	60.838	49.974
Austria	39.902	38.370
Italy	42.432	36.199
Germany	20.547	20.150
Spain	36.395	18.782
Finland	15.799	14.772
Romania	18.028	14.494
United Kingdom	5.390	5.928
Portugal	15.723	5.897
Croatia	6.853	5.307
Latvia	2.530	4.381
Slovakia	4.359	4.324
Greece	5.543	3.963
Slovenia	4.503	3.868
Bulgaria	3.942	2.828
Poland	2.140	2.560
Czechia	2.000	1.869
Ireland	0.681	0.692
Lithuania	0.454	0.602
Belgium	0.370	0.270
Hungary	0.259	0.220
Luxembourg	0.115	0.086
Netherlands	0.100	0.061
Estonia	0.035	0.026
Denmark	0.019	0.018
Total EU 28	350.976	300.707

Source: Eurostat

Figure 1.10: Hydraulic gross electricity production by country in the EU. Source: Eurostat [11].

As a part of hydro power; wave, current and tidal power have not had the same development as the traditional hydraulic power. Still in the first stages of development, these types of renewable energies have been used in Spain mainly in research projects, although there are some wave and current power plants, being one example of wave power energy plant at Mutriku (figure 1.11), in the Basque Country, of 296 kW and an annual production of around 250,000 kWh [12]. Even if the development of these type of technologies has not been as great as for the solar or wind ones, Spain has a great potential in terms of marine power generation. The country has around 6000 km of coastline and a great 'wave energy resource', which could be exploited for energy generation. Just in the northern coast, the annual wave power is around 400 MWh/m [13].

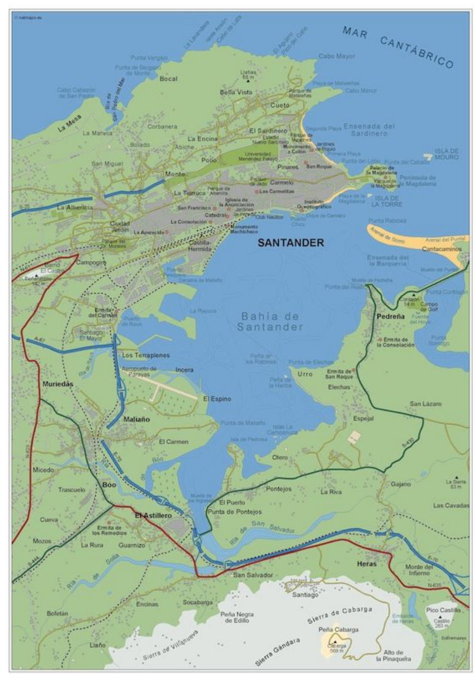
Figure 1.11: Mutriku wave power plant. Source: Diario Renovables [12].

Regarding the global increasing needs of energy and the problem with climate change caused by greenhouse gases emissions and, more specifically, this same issues in Spain. The aim of this project is to decide, for a specific place in Spain, which form of renewable energy source will perform the best at that location, choosing between solar energy, wind energy and marine power (tidal and wave energy). This place will be the Port of Santander, located in the north of Spain. For analyzing which of the alternatives is the best for the chosen location, historical data from the most important parameters for each type of energy resource will be gathered, analyzed and then compared with the rest of the options. This way, it will simulate the first steps of analysis that this kind of project would require in order to choose which option is the best.

2. Background

Santander is a city located in the northern coast of Spain (figure 2.1), surrounding the bay with the same name (Bay of Santander). As capital of the region of Cantabria, it has a population of around 170,000 inhabitants, which is low compared to other nearby capital cities such as Bilbao (345,000) or Oviedo (220,000). As a capital city, Santander has important private and public institutions such as the University of Cantabria, Santander Bank, the government of Cantabria... Also, one of the main economic activities in the city is tourism, due to the coastal location. Another important feature of the city, according to its location, is the port.

(a) Location of Santander within Spain.



(b) Map of Santander's area.

Figure 2.1: Santander in maps.

Santander's port was founded by Romans in 19 B.C. with the name of *Portus Victoriae*. It is located inside the Bay of Santander as in that place the sea power is not as strong as in the open sea, so the boats would have a 'natural protection' when reaching the port. For the next centuries, and until our time, it has been a key location in the north of Spain referred to transportation of people and goods. Because of this, the port increased its size, expanding around the bay and influencing in the economic activities of other villages beyond Santander, as it is the case of El Astillero, which is a town in the south that became the place where the ships from the port went for repairs and maintenance.

Nowadays, the port is one of the main connections for passengers and cargo from Spain to the UK, it is the 3^{rd} port in Spain in terms of vehicle shipping and the 1^{st} in terms of vehicle shipping without any nearby automobile factory. So, even though it is a rather small port, it has a remarkable relevance at a national level. So that, the Port of Santander contributes a 10.56% to the GDP of the region and 9.60% of the employed population have a job related to the port [14]. In total, the Port of Santander has connections with countries in every continent which makes it one of the most important ports in northern Spain with Bilbao.

According to the growth of the economic activity of the port, the energy demand has also increased. For this reason, in 2018 the Spanish electric company *Viesgo*, started the construction of a new electrical substation to satisfy the increasing energy demand [15].

But, for a few years from now, a new idea has emerged to fulfill the increasing energy demand. Instead of building new electrical substations or increasing the capacity of the power lines that arrive to the port, the Port Authority believes that they could face part of the demand with energy produced in the port. This means studying which form of energy production would be the best to use within the port, obtaining a good energy production without interfering with the normal activity of the port. Furthermore, taking into account all the issues stated in chapter 1 that society faces nowadays, referred to the greenhouse gasses emissions in the energy production, this energy production should be performed using renewable energies in order to minimize the environmental impact.

3. Method

In order to choose which of the alternatives is the most suitable for the renewable energy production in the Port of Santander, a research work will be carried out in the form of a case study.

First of all, a bibliography study will be performed, starting with solar energy and followed by wind energy and marine power. For each of the subsections, there will be a series of parts addressed. The first one will be an introduction, explaining what is the actual state of development of the technology, as well as explaining its historical development from the first use until nowadays, introducing some actual examples of power plants using that specific energy source. In this part, also, the causes that are responsible for the energy production will be addressed too. This means, explain how the solar radiation reaches the Earth and how it is distributed depending on the place, for example. Following the introduction, there will be an explanation of how the energy is obtained. This is, explaining how the energy is converted from the source into electrical energy for its use. This section will contain equations if they are necessary to obtain the total power that can be generated and, furthermore, will explain which parameters influence in the amount of energy that is generated. This way, the equations and parameters shown in this part will be used later for comparing between the alternatives. Finally, the main issues that each technology faces will be addressed.

After the theory review, there will be a presentation of all of the data gathered for the analysis of the alternatives. This data will be obtained directly from the weather station of the Santander's Port Authority. All the data collected will correspond to the significant parameters for each of the technologies reviewed in the theory section. This data will contain historical measures of up to 10 years ago and will be analyzed in order to obtain the mean values for a specific period of time (yearly, monthly...) according to the needs. Afterwards, this data will be used for analyzing the potential of exploitation that each energy source has for this certain location, although no optimization work will be done in this project.

Besides the data analysis, there will be a discussion section in which all the results obtained from the data analysis will be summarized and compared between them, so the best alternative is decided. The main points that will be discussed will be:

- Total capacity and energy that could be produced using each of the alternatives.
- Difficulty building the infrastructure of the different power plants.

- Compatibility with the everyday activities at the port.
- Social concerns regarding the installation of the power plant.

Finally, the best alternative will be chosen in the conclusion section. As well, a summary of the pros and cons regarding the election will be performed, recapitulating why it was selected before the other alternatives. Furthermore, the emplacement of the power plant will be addressed broadly, showing which places would be suitable within the port for locating it.

The boundaries considered for the port will be the land facilities in the Bay of Santander, but also the anchorage area outside the bay. Looking at figure 2.1b, these places would be the west areas of the bay (where the coast has a polygonal profile) that represent the land area and the sea in the north-east of the map which is the location of the anchorage site. The bay area can be also considered for the project but considering that the new power plant will not interfere with the normal operation of the activities in the place. Ultimately, the weather conditions gathered by the weather station will be considered the same for the whole port boundaries explained at the beginning of this paragraph.

4. Theory on solar, wind and marine power

4.1 Solar energy

The sun is the sustenance of life and its importance has been known since ancient times, where many civilizations worshipped sun gods. As for environmental influence, the sun is responsible of the heat coming to the Earth, that causes most of the atmospheric phenomena such as the air currrents that produce wind and ocean currents, storms and hurricanes... It also influences the water cycle, providing the necessary heat for the water to evaporate and then start the whole cycle.

The incoming solar radiation that reaches the Earth is 174 PW which is either reflected back or absorbed by land and oceans. From this incoming radiation, the average power density of solar radiation is 170 W/m^2 for oceans and 180 W/m^2 for continents [16]. The difference in power density between oceans and land happens because the water reflects more radiation than the land. At night, around 70% of the radiation absorbed is then radiated back into space so the planet is kept at a regular temperature.

According to all this data, the International Energy Agency suggested that the sun could be the largest electricity source by 2050, generating as much as 16% of the world's electricity demand only via photovoltaic power plants, and 11% from concentrated solar power (CSP) [17].

There are many different methods in which humans can take advantage of the solar radiation, the most common ones are solar heating, photovoltaics, concentrated solar thermal energy, molten salt power plants, solar ponds... The development pace of these techniques has increased in the last years due to the importance that climate change has taken in the global scene and because of the most important strength of solar energy: its inexhaustibility. Among other strengths of the solar power, there is the possibility of harnessing sunlight in both small and large applications, using the building's roofs to install PV panels, so also the need to integrate the panels into the grid is eliminated as the production is done in the same place where the consumption takes place.

4.1.1 Photovoltaics

A solar panel converts sunlight radiation into electricity through the photovoltaic process. To explain how does this process work, it is necessary to talk first about the light absorption in materials and the excess carrier generation. When light (flux of photons) reaches the surface of a material, part of it is reflected while other part is absorbed. The light absorbed interacts with the particles of the material. This interaction must conserve the energy and momentum. If the interactions cannot satisfy the conservation laws, then the photons from the light are not absorbed, so the material is transparent. Otherwise, if the interactions can satisfy the conditions, then the photons are absorbed by increasing the energy of the material particles. These interactions are divided depending on what the interaction is done with. According to this, there are three types of interactions: with the lattice, with free electrons and with bonded electrons.

The interactions with the lattice are basically low energy photons interacting with the particle nucleus. On the other hand, interactions with free electrons happen when their concentration is high. Even though, both of the interactions produce an increase in the kinetic energy of the particles, resulting in an increase of the temperature of the material.

The most important interactions for photovoltaics are the interactions with bonded electrons (figure 4.1). These interactions occur when high energy photons interact with electrons that have a lower energy bond, freeing the electron from the bond so it can move in the material, leaving a hole in its former location. When this happens, light produces some excess carriers, considering them as the pair electron/hole [18].

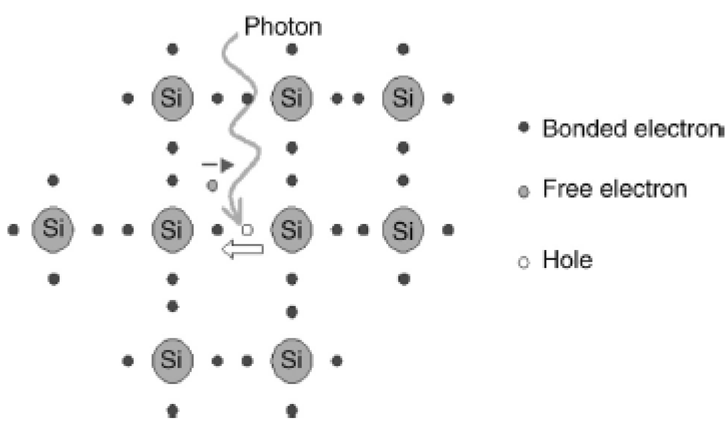


Figure 4.1: Generation of electron-hole pairs. Source: A Comprehensive Guide to Solar Energy Systems [18].

4.1.1.1 Bandgap

PV cells are made of semiconductor material. This type of material works in a special way, having two different bands [18]:

- Valence band: formed by all possible energies of bonded valence electrons, having an energy W_v.
- Conduction band: formed by all possible energies of free electrons, having an energy W_c.

Considering these two bands, the difference in energy between them is called bandgap (W_g), which is one of the most important parameters of a semiconductor, calculated by the expression: $W_g = W_c - W_v$. So that, when light radiation interacts with a semiconductor, there are two different possibilities. If the energy of the irradiation is lower than the bandgap ($hv < W_g$), the photons are absorbed by lattice and free carriers while, if the photon energy is higher than the bandgap ($hv > W_g$), absorption coefficient increases with the photon energy and interband absorption takes place. With this last type of interaction, the pair electron-hole is generated as shown in figure 4.1. Furthermore, if the photon energy is too high, it will be converted into heat so, in the end, only a part of the radiation spectrum is used for carrier generation while the other is either not absorbed (low energy) or transformed into heat (high energy). This is very important in the case of multi-junction PV cells as materials with the higher bandgap are located in first place so the radiation they do not absorb can be absorbed by the next material with a lower bandgap as stated in figure 4.2.

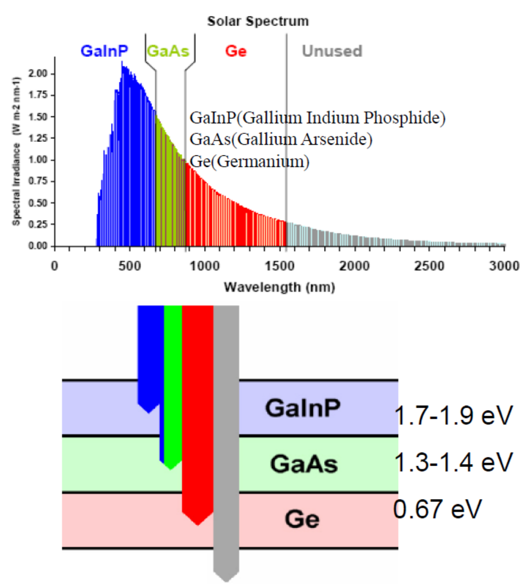


Figure 4.2: Absorption of radiation in a triple-junction cell. Source: Alternative Energy Sources and Their Applications course documents [16].

4.1.1.2 PN structure

The purpose of solar cells is to create an electrical energy source, this is an 'inhomogeneous structure with an internal electric field' [18]. To achieve this goal, solar cells implement the photovoltaic effect which can be understood as the conversion of sunlight radiation into electrical energy by using semiconductor materials. When excess carriers appear, the thermodynamic equilibrium is broken so, in order to reach the equilibrium again, free electrons and holes recombine. In a homogeneous material, excess carriers that may generate because of radiation recombine rapidly so most of the energy is transformed into heat. To create the 'inhomogeneous structure with an internal electric field', there are a few structures that may achieve this goal, being the main one the PN junction (figure 4.3).

When incident light reaches the surface of the material, the electron-hole pairs are generated. Holes diffuse from the p-doped zone to the n-doped zone through the region boundary and electrons diffuse from the n-doped zone to the p-doped. This way, there is a negatively charged region near the boundary in the p-zone while the region near the boundary in the n-type region is charged positively, creating a potential difference between them. Hence, the goal of obtaining an 'inhomogeneous structure with an internal electric field' is fulfilled with this PN structure. Most of the solar cells are built following this structure.

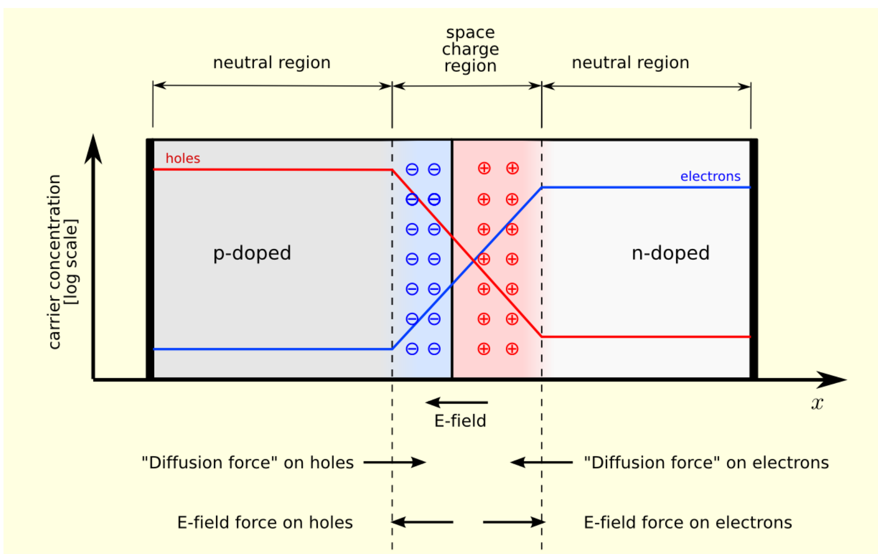


Figure 4.3: Schematic PN junction. Source: Alternative Energy Sources and Their Applications course documents [16].

Also, the range of radiation that the cell can absorb depends on its bandgap. Solar cells have a bandgap that allow them to absorb photons within the range of visible light of the solar spectrum. If the photon has an energy equal or higher than the bandgap, it can be absorbed. The bandgap value that allows a solar cell semiconductor to absorb photons within the visible light range is 1.43 eV [19]; looking at table 4.1, this bandgap value matches the value of gallium arsenide. It would be then obvious to use this material for all solar cells, but this material has environmental concerns in addition to being more expensive than silicon. Although it has a lower bandgap, which implies a worse performance, silicon has proven to be the most efficient in terms of cost and energy generated. Each photon with enough energy is absorbed by an electron in the silicon, so it increases its energy compared to the other electrons. In a PN junction, it is possible to create an electric current because of this increase in potential due to its special structure. This current is produced at a fixed voltage specific for every semiconductor: the cell voltage or open-circuit voltage. The open-circuit value for silicon is 0.6 V.

Table 4.1: Bandgap for different semiconductors. Source: Solar Power Generation [19].

Semiconductor	**Bandgap (eV)**
Silicon (Si)	1.11
Cadmiom telluride ($CdTe$)	1.44
Gallium arsenide ($GaAs$)	1.43
Copper indium gallium diselenide ($CuInGaSe_2$)	0.9 - 1.7

4.1.2 Solar energy performance

So, all in all, it is clear that solar cell's performance depends on the solar radiation that reaches the surface. The higher the radiation, the higher the output, although very high radiation values could have a negative effect in the output voltage, decreasing as shown in figure 4.4. Furthermore, the ambient temperature also affects the performance of the solar cells, even needing a cooling system in places with high temperatures [20]. This way, it is possible to think that the better output is obtained when the radiation values are high but the temperature does not increase a lot. This parameters will be taken into account when comparing the performance of each of the three technologies for the project later in the discussion.

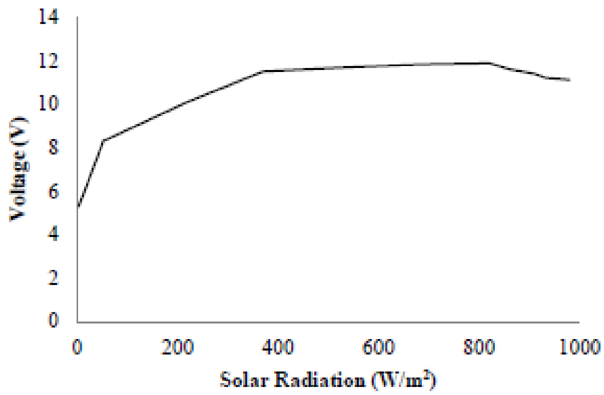


Figure 4.4: Impact of solar radiation on voltage. Source International Research Journal of Advanced Engineering and Science [20].

Even though, solar energy has also its downsides. Solar radiation has a low power density so, large areas of land have to be occupied with solar panels in order to produce as much power as possible. For example, Chinese companies pretend to build a giant solar farm of 1 GW of capacity in a 2500 ha of area in the Chernobyl exclusion zone [17]. So, this means that almost 25 km^2 of land are needed to produce one gigawatt of power, when other types of power plants produce a few gigawatts in much less space. As well, not every place in the planet has the same capacity for solar power generation, this way, places near the equator are more suitable for solar power plants rather than places far from it where the sun radiation reaches the surface less directly (figure 4.5). Furthermore, solar energy production is not constant, stopping during night time and depending on the weather conditions each day. So that, an energy backup is needed for the times that solar power plants are not able to produce it. These backups could be either other type of renewable energy or a fossil fuel power plant.

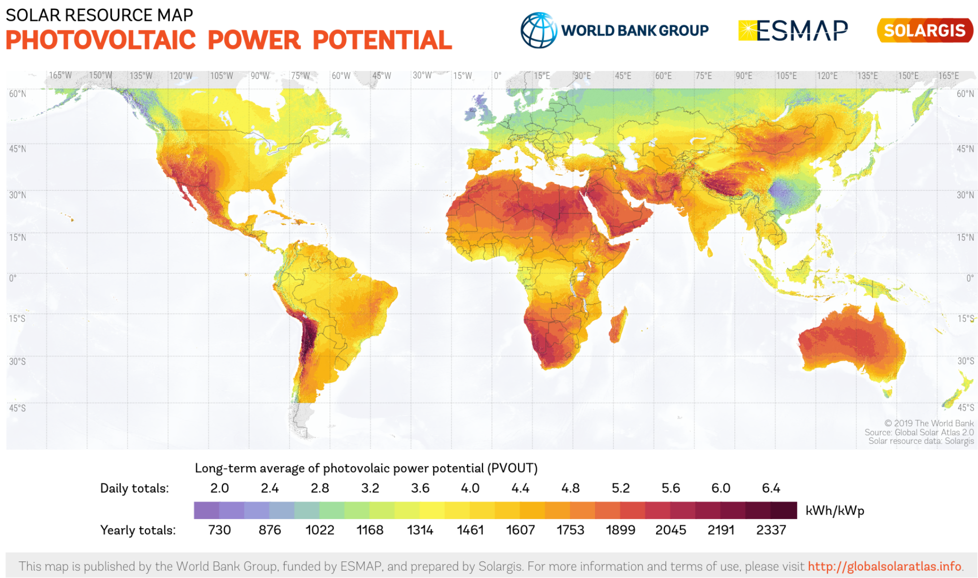


Figure 4.5: World photovoltaic electric potential. © 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis [21].

4.2 Wind energy

Wind energy is basically a converted form of solar energy. From the total solar power received by the Earth, 2% is converted into wind energy and 35% is dissipated above 1000 m from the surface. Even though, the energy remaining is 20 times larger than the global energy consumption (around 63 MW) [22]. As it happened with solar energy, wind energy is inexhaustible and available in every place in the world, but the cost of producing the same energy is cheaper in the case of wind energy than solar.

Wind is probably one of the most ancient forms of energy that have been used by humans. It is possible to track the use of wind energy as early as 4000 B.C. when the Chinese attached the first sails to their boats that helped moving them instead of just using the human power to row their way. It could be said that ancient China civilization was the first to use wind power, as they also started using windmills at least 1800 years ago for water pumping and grain grinding. These ancient windmills had a vertical axis instead of the horizontal axis windmills that are commonly seen nowadays. This last type was developed in Europe during the late 12^{th} century.

Wind is generated as a result of atmospheric pressure gradients, producing the movement of air masses from high pressure places to low pressure regions. The higher the pressure difference, the greater the wind. There are three factors that influence in the generation and movement of winds [23]:

1. **Uneven solar heating.** It is the most important of them and it depends on four reasons.

    (a) The surface of the Earth at the equator receives perpendicular radiation while the poles receive the sun rays in a more parallel way. For this reason, the equator receives much more energy per unit area, decreasing the value when getting nearer to the poles. This unevenness produces a temperature gradient between the poles and the equator, causing the hot air in the equator to rise and move towards the poles so, consequently, cold air from the poles flow to the equator. If the Earth's rotation is not considered, the wind flow would correspond to a single convection cell or 'meridional circulation' shown in figure 4.6.

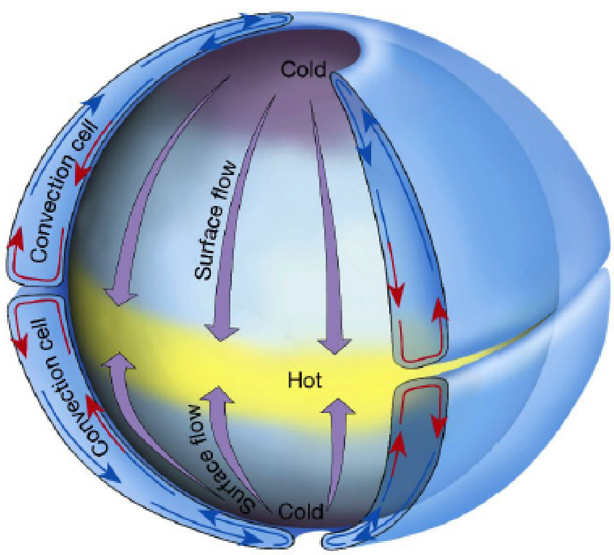


Figure 4.6: Simple, single cell atmospheric convection in a non-rotating Earth, without Coriolis force effect. Source: Alternative Energy Sources and Their Applications course documents [22].

    (b) The Earth's axis is tilted 23.5º so, during the orbit around the sun, it results in cyclic uneven heating as some places are more exposed to solar radiation than others.

    (c) The surface of the Earth is covered with different materials that have different absorbing and reflecting rates. This way, places covered in snow have a higher reflectance than, for example, grasslands; resulting in lower temperatures.

(d) The surface of the Earth has different geographical features like mountains, gorges, plains... that affect in the amount of solar radiation that certain places receive.

2. **Coriolis Force.** The Earth's rotation is the cause of the Coriolis force, which deflects the direction of atmospheric movements, including wind. In the northern hemisphere, the wind is deflected to the right and in the southern hemisphere to the left. Coriolis force depends also on the latitude, being zero at the equator and increasing with latitude until reaching its maximum at the poles. Besides, the faster the wind, the greater is the effect of Coriolis force. Applying this to the single cell model obtained because of uneven heating, it becomes a three-cell model in each hemisphere: the Hadley cell, the Ferrel cell and the Polar cell (figure 4.7).

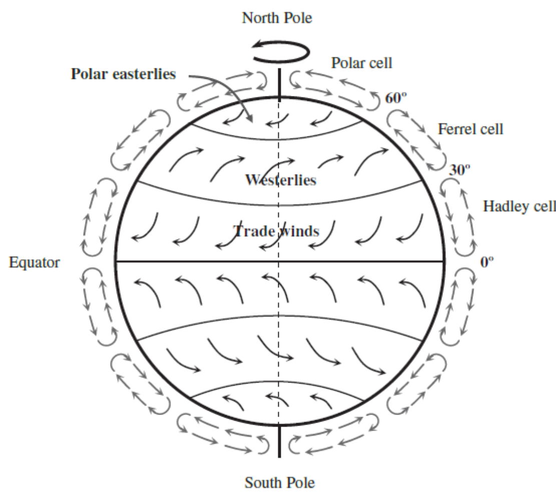
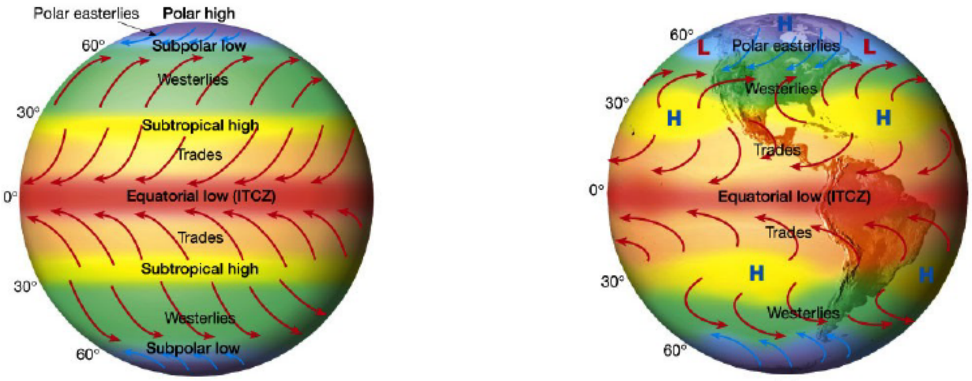


Figure 4.7: Idealized, three-cell atmospheric convection in a rotating Earth. Source: Wind Power Generation and Wind Turbine Design [23].

3. **Local geography.** The frictional drag and obstruction in the Earth's surface slows wind speed and creates the wind shear phenomena (figure 4.8). Some geographic features can increase the wind speed instead of slowing it. Also, the speed increases with the altitude; approximately, when doubling the height, wind speed increases by 10%.



(a) Idealized winds generated by pressure gradient and Coriolis force.

(b) Actual wind patterns caused by land mass distribution.

Figure 4.8: Comparison between three cell model and the actual wind patterns. Source: Alternative Energy Sources and Their Applications course documents [22].

4.2.1 Wind power

Wind energy is basically the kinetic energy of an air flow. For this reason, it has a series of characteristics that influence the amount of energy that can be converted into electrical energy.

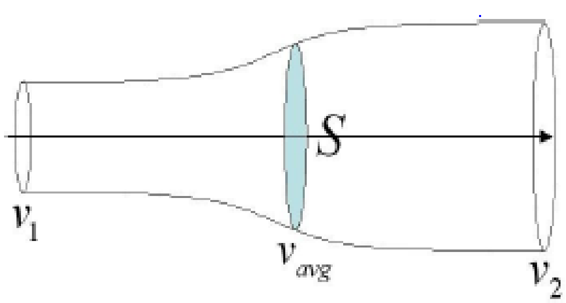


Figure 4.9: Ideal outline of the airflow in a wind turbine. Source: Alternative Energy Sources and Their Applications course documents [22].

First of all, wind has a certain power, which is possible to obtain by differentiating the kinetic energy with respect to time. Considering the ideal outline of a wind turbine shown in figure 4.9, where the area covered by the turbine blades is S; the kinetic energy of wind is:

$$E = \frac{1}{2}m\bar{v}^2 = \frac{1}{2}m(v_1^2 - v_2^2) \tag{4.1}$$

Where m is the air mass and v is the mean wind speed. Also, wind energy can be considered as:

$$dE = F * dx \tag{4.2}$$

For combining these two expressions, it is necessary to define the expression of wind force:

$$F = ma = m\frac{dv}{dt} = \dot{m}\Delta v = \rho S v(v_1^2 - v_2^2) \tag{4.3}$$

Where $\dot{m}$ is the air mass flow defined by (regarding at figure 4.9):

$$\dot{m} = \rho A_1 v_1 = \rho S v = \rho A_2 v_2 \tag{4.4}$$

The wind power will be the differentiate of the kinetic energy with respect to time (introducing equations 4.2 and 4.3):

$$P = \frac{dE}{dt} = F\frac{dx}{dt} = Fv = \rho S v^2(v_1^2 - v_2^2) \tag{4.5}$$

Being v the mean wind speed defined by:

$$v = \frac{1}{2}(v_1 + v_2) \tag{4.6}$$

But, also, wind power can be obtained differentiating the expression 4.1:

$$P = \frac{dE}{dt} = \frac{1}{2}\dot{m}(v_1^2 - v_2^2) \tag{4.7}$$

If expression 4.6 is introduced in equation 4.5, a new power expression is obtained:

$$P = \frac{1}{4}\rho S(v_1 + v_2)(v_1^2 - v_2^2) = \frac{1}{4}\rho S v_1^3\left(1 + \left(\frac{v_2}{v_1}\right) - \left(\frac{v_2}{v_1}\right)^2 - \left(\frac{v_2}{v_1}\right)^3\right) \tag{4.8}$$

Where S can be defined as $S = \pi r^2$ (r is the length of the blade), so the equation ends up being:

$$P = \frac{1}{4}\rho\pi r^2 v_1^3\left(1 + \left(\frac{v_2}{v_1}\right) - \left(\frac{v_2}{v_1}\right)^2 - \left(\frac{v_2}{v_1}\right)^3\right) \tag{4.9}$$

Taking $\frac{v_2}{v_1}$ as a variable and differentiating the equation 4.9 with respect to it, it is obtained that $\frac{v_2}{v_1} = \frac{1}{3}$. Substituting this value in expression 4.8, the expression for the maximum wind power that can be extracted from a wind current is obtained:

$$P_{max} = \frac{16}{27}\frac{1}{2}\rho\pi r^2 v_1^3 = \frac{16}{27}P_{wind} \tag{4.10}$$

Analyzing equation 4.10, it is clear that the theoretical maximum wind power that can be extracted depends on the inlet air speed and the area covered by the turbine's blades. This power generation will be done with a maximum efficiency of $\frac{16}{27}$ or, in percentage, 59.3%. This value is known as the Betz's law and it applies for both wind and water turbines. The reason why a turbine cannot work at a 100% efficiency is because that would imply that it extracts all of the energy from the air flow; this would mean that the air behind the turbine would have no speed, which is false. Furthermore, the variations in wind speed affect greatly to the power generated as this parameter is raised to three. The same happens with the blade's length, which is raised to two. Also, the air density can affect the total power generation, the lower the density, the lower the power generated. Knowing that the air density decreases as height above sea level increases, it can be deduced that sea-level wind turbines will be more efficient than the ones located in mountains (although it may be an almost imperceptible difference, depending on the mountain height).

For evaluating the wind resource at a particular site, it is used an index called wind power density, which is the available wind power in airflow through a perpendicular cross-sectional unit area in an unit time period [23]. There are different wind power classes for different heights depending on the wind power density and the mean wind speed (table 4.2). These classes are an indicator of the viability of a wind plant in a certain place, for example, a class rating of 4 or higher makes the location suitable for a wind power plant.

Table 4.2: Classes of wind power density. Source: Wind Power Generation and Wind Turbine Design [23].

	10 m height		50 m height	
Wind power class	**Wind power density (W/m^2)**	**Mean wind speed (m/s)**	**Wind power density (W/m^2)**	**Mean wind speed (m/s**
1	<100	<4.4	<200	<5.6
2	100-150	4.4-5.1	200-300	5.6-6.4
3	150-200	5.1-5.6	300-400	6.4-7.0
4	200-250	5.6-6.0	400-500	7.0-7.5
5	250-300	6.0-6.4	500-600	7.5-8.0
6	300-350	6.4-7.0	600-800	8.0-8.8
7	>400	>7.0	>800	>8.8

4.2.2 Other wind characteristics

4.2.2.1 Wind speed

Wind speed is one of the most important parameters in wind power generation, as the total amount of power generated depends on the cube of its value as seen in section 4.2.1. It is a random parameter that varies throughout the day, being higher normally during midday as it is proportional to the strength of sunlight. Depending on the place, wind speeds are very different and there is no correlation between them.

4.2.2.2 Weibull distribution

For a certain place, the variation in wind speed is well approximated using the Weibull distribution (figure 4.10). The distribution is represented by the formula:

$$W(\lambda, x, k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{(}k-1)exp\left(-\left(\frac{x}{\lambda}\right)^{k})\right) \tag{4.11}$$

Where λ is the scale factor, k is the shape factor and x is the mean wind speed. The most probable wind speed is obtained by doing $v = 2\frac{\lambda}{\sqrt{\pi}}$ [22].

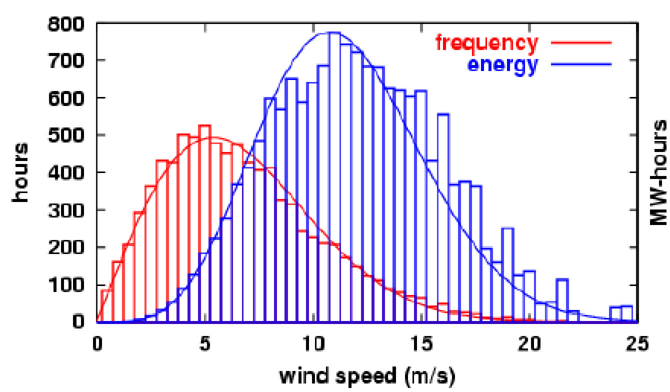


Figure 4.10: Weibull distribution for a certain place. Blue represents energy and red represents the Weibull distribution of wind speed over time. Source: Alternative Energy Sources and Their Applications course documents [22].

4.2.2.3 Wind turbulence and gust

Wind turbulence and gusts are both referred to sudden changes in wind speed. They have a strong impact on the power output and, in the case of wind gusts, it may cause an excess of power output, higher than the level the turbine was design for. Also, they have effects in the turbine itself, causing fatigue in the materials that may lead to a turbine failure. Predicting wind gusts and selecting places where turbulent wind is uncommon is highly recommended when planning a wind power plant because all the issues described before.

4.2.2.4 Wind direction

Another important parameter when placing a wind power plant is the dominant direction of the wind in that specific place. Wind direction data is recovered for long periods of time so a statistical analysis can be performed in order to find which directions are dominant.

This data is used to summarize the wind direction data in a special type of diagrams called wind roses. Wind roses show the dominant wind directions for a region in specific periods of time such as years or months. They can also be represented along with wind speed data to show which direction is the dominant and from which direction comes the wind with the highest speed. Figure 4.11 shows the wind rose for Stockholm, indicating that the dominant (and strongest) winds come from the south and sout-west direction.

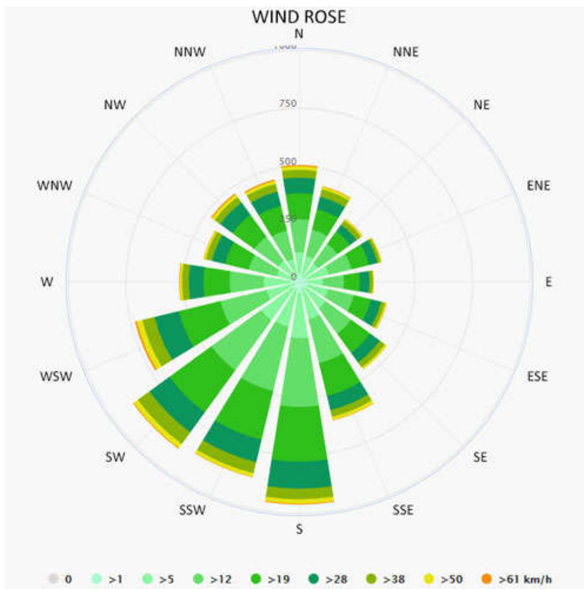


Figure 4.11: Wind rose for Stockholm. Source: Boat the Globe [24].

4.2.2.5 Wind shear

Wind shear is described as the phenomenon that makes the wind speed increase with altitude. According to practical data, it is said that wind shear follows the 7^{th} root law. This way, considering P_{wind} obtained in equation 4.10, the power generated at a certain altitude (taking g as the reference altitude and h as the altitude used for the problem) will be:

$$\frac{v_h}{v_g} = \sqrt[7]{\frac{h}{g}} \Rightarrow P_h = \sqrt[\frac{7}{3}]{\frac{h}{g}} P_g = \left(\frac{h}{g}\right)^{0.43} P_g \tag{4.12}$$

4.2.3 Wind turbines

As stated at the beginning of this section, wind energy has been used for thousands of years. Windmills and early wind turbines used for water pumping have been improved until the modern wind turbine design nowadays. Modern wind turbines are machines that convert the kinetic energy in the wind into mechanical energy for then transforming it into electrical energy. There are several ways of classification of wind turbines but the main ones are depending on their axis orientation, the wind flowing direction, their capacity and their location.

4.2.3.1 Horizontal-axis and vertical-axis turbines

This classification is made depending on the orientation of the rotating axis of the turbine. Horizontal-axis wind turbines (HAWT) are the most common type, in which the rotating axis is parallel to the ground and wind flow. This type of turbines is characterized by high turbine efficiency, high power density and low cost per unit power output [23].

Vertical-axis wind turbines (VAWT) are more flexible to wind directions, accepting any direction so there is no need to control the axis direction (yaw control). These turbines have their rotating axis perpendicular to the ground and, due to this, their maximum height is limited. Furthermore, they need an external energy source to start the rotation of the blades until they keep rotating because of the wind. The downside of this type of turbines is the low efficiency and limitation on high power applications.

(a) Horizontal axis wind turbine. Source: BBC [25].

(b) Vertical axis wind turbine. Source: Inhabitat [26].

Figure 4.12: Comparison between HAWTs and VAWTs

4.2.3.2 Upwind and downwind turbines

Depending on the flow of air through the turbine, there are upwind and downwind turbines.

Upwind turbines face the wind, this means that the air flow passes through the blades first. This avoids the wind being distorted by the wind tower as the rotor faces the wind.

Downwind turbines have a contrary air flow, from behind the rotor. This makes the wind turbine blades more flexible but, the wind power output is more variable as well as causing fatigue in the turbine.

4.2.3.3 Turbine capacity

Regarding the total capacity of the wind turbine (figure 4.13), it can be divided into five groups:

1. **Micro wind turbines** have a power lower than a few kilowatts.
2. **Small wind turbines** have a power lower than 100 kW. Are mostly used for residential and farming applications.
3. **Medium wind turbines** are the most extended with rated powers between 100 kW and 1 MW. They are used in both on-grid and off-grid systems.
4. **Large wind turbines** up to 10 MW are the most common in wind farms.
5. **Ultra-large wind turbines** are currently under development, but the first prototypes have a capacity greater than 10 MW.

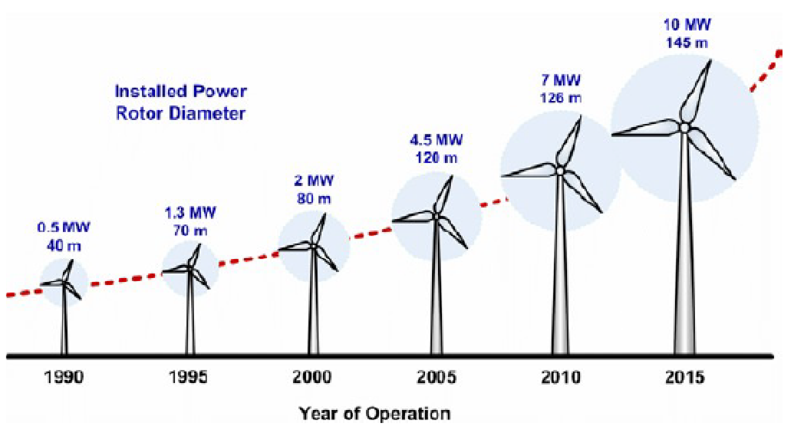


Figure 4.13: Wind turbine capacity throughout the years. Source: Alternative Energy Sources and Their Applications course documents [22].

4.2.3.4 Onshore and offshore turbines

Onshore wind turbines have lower costs of foundations and building, easier integration in the electrical grid and easier access for maintenance. On the other hand, offshore wind turbines have a better wind resource and can obtain a higher power output compared to the onshore ones as they can normally operate more hours. Also, offshore wind turbines have less restrictions to deal with. For example, turbine noise is a great concern in onshore wind turbines (more if they are located near a residential area) but it does not present any problem for an offshore turbine.

4.2.4 Wind energy concerns

Wind energy, as it happened in section 4.1.2 with solar energy, has its downsides. Many of them are referred to the environmental and visual impact of wind turbines. There have already been problems with citizens that did not want to have wind turbines in a mountain range near their city/village because of the visual impact; but there are also regulations regarding the turbine noise that restrict the places where wind power plants can be located avoiding issues to the near population. The noise caused by wind turbines is a combination of the aerodynamic noise from the rotating blades and the noise from the gearboxes inside the turbine.

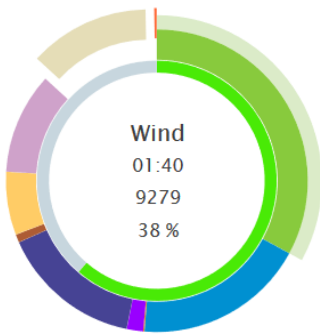
Furthermore, wind turbines have environmental impacts that need to be considered. As large wind power plants contain a lot of turbines, they can interfere in bird migration routes and kill some birds as the wind tips of a large size turbine can reach a speed of 70 m/s [23]. To avoid this, studies of the birds migration routes have to be done to make sure that the place where a wind farm is being installed does not cause any threat to the birds.

As stated in section 4.2.2, wind speed is a random parameter that may vary suddenly as it happens in turbulence and wind gusts, which could cause several problems in a wind turbine if they were badly predicted. In the same way, very high wind speeds could be dangerous for a wind turbine. In the case of winds faster than 80 - 90 km/h, most of the wind turbines have to stop their activity to avoid any kind of problems derived from the high speed winds. For this reason, wind turbines cannot operate always, they depend on there being enough wind speed, but not excessive. Also, to avoid wind turbines interfere with the airflow that reaches another wind turbine nearby, specific distances have to be maintained:

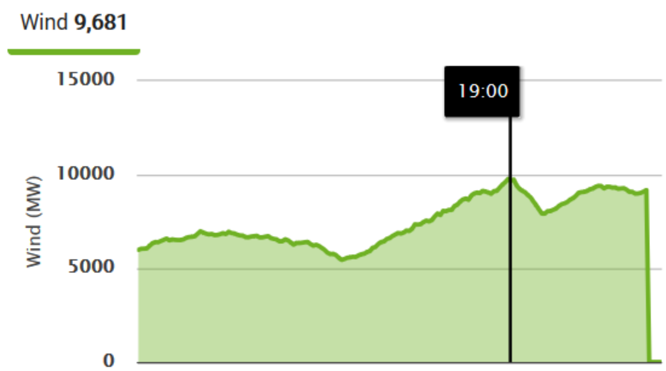
- In the wind flow direction, the separation between turbines must be 8 - 12 times the rotor blades diameter.
- Perpendicular to the wind flow direction the separation must be around 2 - 4 times the rotor blades diameter.

Besides, considering a normal operation of the turbine, the different components have to resist adverse climate conditions (that include extreme changes in temperature) throughout their whole lifetime. For this reason, wind turbines need a thermal control system for maintaining the components inside the turbine within a specific range of temperatures. The opposite can happen in very cold climates: heating systems may be required to heat the blades and avoid the ice formation or raise the temperature inside the turbine to prevent the malfunction of the electronics or the oil lubrication.

Finally, the integration of wind turbine into the electrical grid network is also a challenge. Due to the intermittent energy production of wind farms (only possible when there is enough wind), electrical systems need to be prepared to allow the energy produced by wind into the network whenever it is possible, but they have also to be prepared to supply that energy from other sources in case there is no wind resource at an specific moment. This is why it is very important to have good weather predictions for wind farm sites, so the wind energy resource can be estimated in advance for planning the total energy generation from the rest of the energy resources. Looking at figure 4.14, it shows the total wind energy production in Spain for April 28^{th} 2020 compared with other energy resources (figure 4.14a) and the power generated per hour (figure 4.14b), showing the variable nature of wind energy.



(a) Wind energy production compared to other sources. Source: REE [27].



(b) Wind power throughout the day. Source: REE [27].

Figure 4.14: Wind energy production in Spain for April 28^{th} 2020.

4.3 Marine power

71% of the planet's surface is covered by oceans which contains huge amounts of mechanical energy [28]. Renewable energy from the oceans can be extracted through various techniques such as wave energy, tidal stream, tidal range, offshore wind energy and ocean thermal energy currents (OTEC) [29]. Although, offshore wind energy was presented in section 4.2 and OTEC systems will not be considered in this project, as they are also a kind of thermal energy. Focusing on wave and tidal power, the main challenges that face both energy resources are mainly related with technology development, infrastructure for the grid connection, cost, environmental impact and legal concerns related to the marine governance. Watching these challenges, it is clear that these technologies are still in the first stages of their development. In the case of tidal energy, there are currently tidal power plants working as real prototypes, while wave power energy is not economically competitive at the time, still needing to develop materials and new technologies that reduce costs and increase efficiency.

4.3.1 Tidal energy

Historically, tide mills have been used for milling grain. In 1966, the first tidal power plant became operational in France (La Rance, figure 4.15a). It was the largest tidal power station until the construction in 2010 of the Sihwa Lake tidal power station in South Korea (figure 4.15b), reaching a capacity of 254 MW and surpassing the 240 MW of La Rance [30].

(a) La Rance tidal power station (France).

(b) Sihwa Lake tidal power station (South Korea).

Figure 4.15: Tidal power stations examples. Source: Power technology [30]

Compared to other renewable energy sources, tidal power is more predictable than wind power and solar energy: the time interval between two consecutive low tides is about 12.5 hours. But, the main issue that it has had over the years has been the high infrastructural cost and the limited amount of spots with enough tidal height difference or flow speeds. Although, in the recent years, the research carried out in this area has brought down tidal power costs to competitive levels.

The tide is 'the periodic oscillation of the sea level caused by the gravitational attraction of the Moon and Sun acting on the water particles in the hydrosphere' [31]. Sun has a lower effect on tides rather than the Moon, as the first one is much further from the Earth than the second. For this reason, high and low tides depend on the position of the Moon as it revolves around the Earth. The Moon's pull is strongest on the part of the Earth directly facing the satellite, if this part is an ocean, the water there bulges towards the Moon.

Tides are different depending on the place. Enclosed seas, such as the Mediterranean, experience very weak tides while other coastal places have larger tidal oscillations. The causes for this difference are related with the water depth, the sea/ocean's geography and the effects of the Coriolis force. Taking the Mediterranean sea as an example, it experiences such weak tides because it has only one way in and out through the Strait of Gibraltar, which allows less water to move in/out.

As it was said before, there are a few places around the world that are suitable for a tidal power station construction. It is compulsory to have a large enough height difference between the high tide and low tide (tidal range) in the case of tidal barrage (or tidal lagoon) power stations or, on the other hand, a sufficient tidal flow velocity for tidal stream power stations. Tidal range in the open sea is not quite large, but it can increase its value in special shores that are semi-enclosed or estuaries. Depending on the tidal range, coastlines can be classified as:

- **Microtidal**. Tidal range below 0.5 m.
- **Mesotidal**. Tidal range between 0.5 m and 4.0 m.
- **Macrotidal**. Tidal range above 4.0 m.

Table 4.3 shows the tidal range of some locations with high tidal energy conversion potential along with the estimated capacity and energy that could produce annually. Looking at the first two locations, they are referred to a certain place in Canada known as the Bay of Fundy, where tidal ranges can reach 16.3 m [31].

Table 4.3: Locations with high potential for tidal energy conversion. Source: Alternative Energy Sources and Their Applications course documents [32].

Location	Country	Range (m)	Average power (MW)	Annual energy (GWh)
Cobesquid	Canada	10.7	20,000	175,200
Passmaquoddy	Canada	5.5	1,800	15,768
Severn river	England	9.8	1,680	14,717
La Rance	France	8.4	349	3,956
Mont St. Michel	France	8.4	9,700	84,972
Kimberlay	Australia	6.4	630	5,519
Mezen	Russia	6.6	14,000	122,640
Khambat	India	7.0	7,000	61,320
Golfo Nuevo	Argentina	3.7	6,600	57,816

As well, tidal range vary in time, having a period of 14.8 days (half the lunar period). During new or full moon, the Moon, Sun and Earth are aligned and the solar tide joins the lunar tide, reinforcing it and causing larger tides. If this event happens when the Moon is closer to the Earth, the increase in the tidal range is greater. Therefore, the largest tides occur in spring when the new/full moon match the lunar perigee.

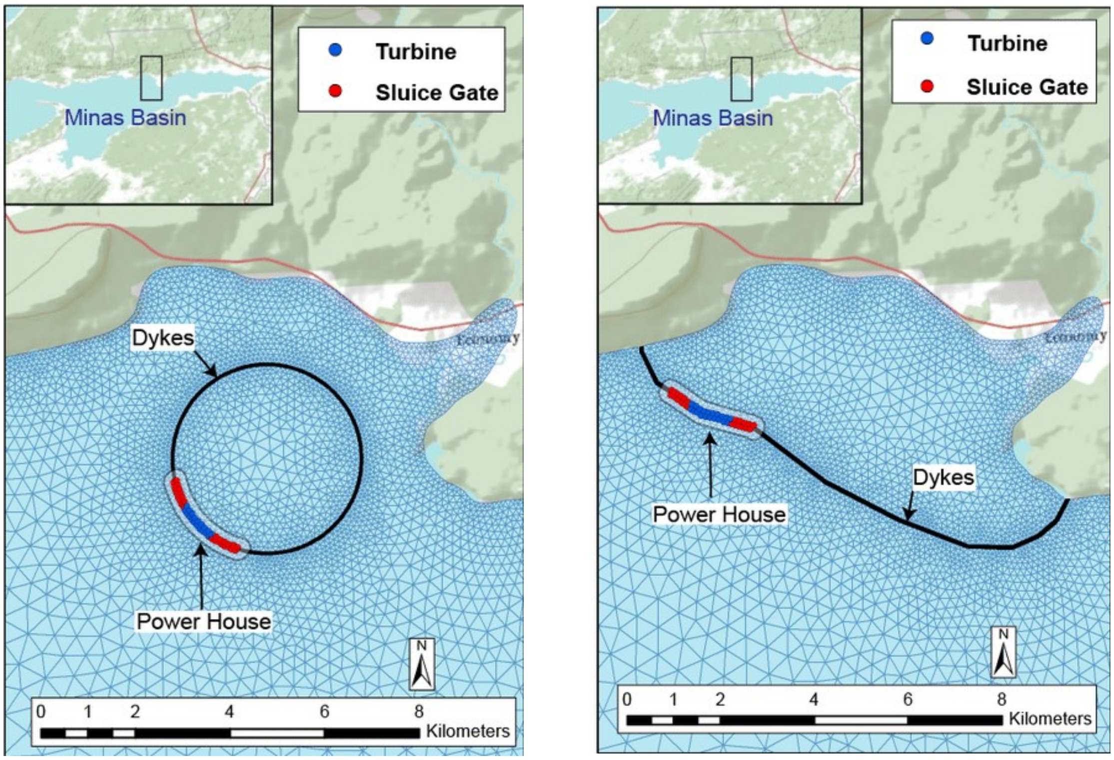
Furthermore, there are other causes in the variation of the sea level in addition to the astronomical events. The weather can also influence the tidal range. When wind blows onshore, it makes the surface level of the sea to rise the shore and the contrary happens if it blows offshore. Also, the atmospheric pressure can produce variations in the sea level: the higher the pressure, the lower the water level. So, in storms, when there is low atmospheric pressure, the water level can rise about 1 cm with every 1 HPa of pressure variation. Considering a normal atmospheric pressure of 1013 HPa, it is possible to assume that in severe conditions, such as the Hurricane Katrina, when the atmospheric pressure dropped to 902 HPa [33], the water level could have risen about 1.11 m additional to the water level due to the astronomical tide and without considering the effect of the wind.

Therefore, there are two ways of obtaining energy using the tides: tidal barrages/lagoons and tidal stream power plants. The first method consists on building a fence in a semi-enclosed body of water such as estuaries. When the water level starts to decrease, the barrage gates close so there is a difference in height between the two sides. Once the low tide is reached, the gates open, leaving the water flow outside through drives turbine-generator groups. The downside is that there are a very limited number of places where a tidal barrage may be built and, also, it causes a great environmental impact. In the case of tidal lagoons, these downsides are a little less relevant as it does not involve 'closing' a whole natural semi-enclosed body of water. The power of a tidal power plant can be obtained using the following equation [32]:

$$P = \frac{\eta g \rho A H^2}{T} \tag{4.13}$$

Where η is the efficiency of the turbines, A the area of the semi-enclosed body of water, H the tidal range and T is the tide period (12.5 h) in seconds.

Figure 4.16 compares the differences between a tidal lagoon and a tidal barrage. The first one clearly shows the main advantage of a tidal lagoon, which is avoiding the entire closure of the Minas Basin site.



(a) Tidal lagoon. (b) Tidal barrage.

Figure 4.16: Comparison between tidal lagoons and tidal barrages applied to the Minas Basin site (Canada). Source: Hydrodynamic Impacts due to Tidal Power Lagoons in the Upper Bay of Fundy, Canada [34].

Tidal stream method consists of installing turbines in the free flow of water caused by the tide and transform the kinetic energy of the flow into electricity. To install an array of tidal stream turbines, several aspects have to be considered such as the tidal stream resource, the connection to the grid and the environmental impact. To have a significant tidal stream, it is necessary to fulfill two conditions: having a significant tidal range and a semi-enclosed body of water. Large tidal ranges do not always imply significant tidal streams, for example in open ocean coasts. Instead, in an semi-enclosed body of water, having a large tidal range implies that large amounts of water must go in and out of the area through the same 'entrance', so significant tidal streams are created. Tidal stream power plants are suitable for areas such as bays, fjords or estuaries.

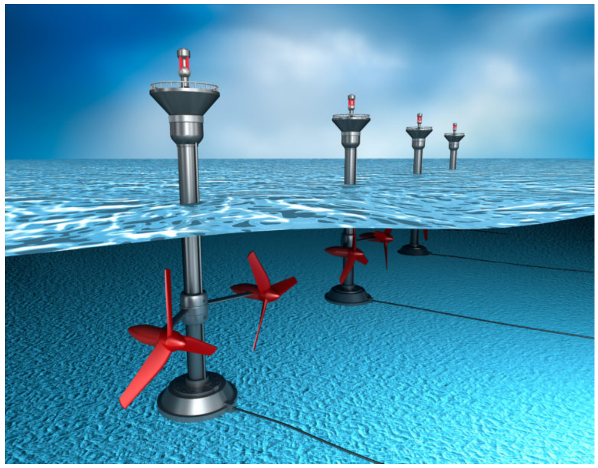
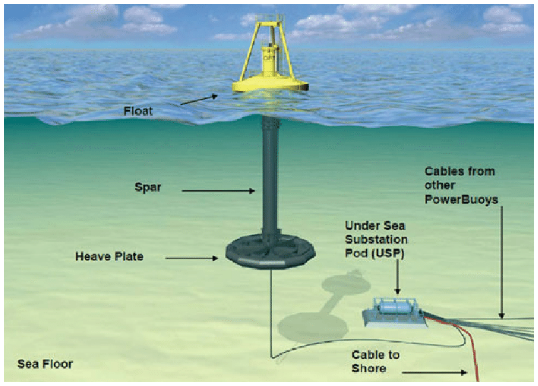


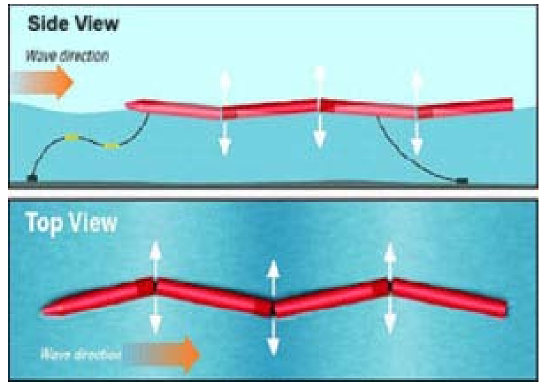
Figure 4.17: Tidal stream power plant. Source: Wood Harbinger [35].

4.3.2 Wave energy

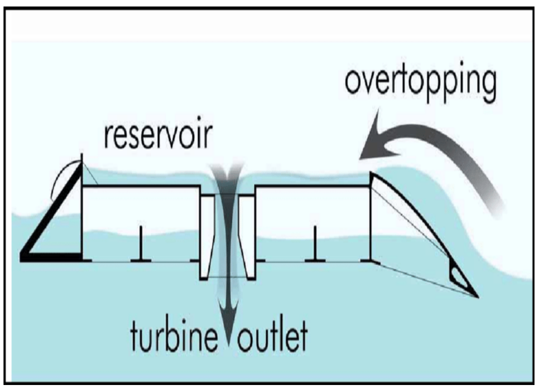
Wave energy converter technology is a field of study where new inventions keep appearing. Such are the amount of new inventions, that there are over one thousand patents of wave energy converters nowadays [31]. Some of these devices are point absorbers, attenuators, overtopping, oscillationg wave surge convertors and oscillating water columns (figure 4.18). Only a small amount of all the devices have reached the full-scale prototype scale, one of them is the Mutriku power plant, which is an oscillating water column converter, that was shown in figure 1.11. The main concerns that must be overcome are related with efficiency, cost and material durability and resistance against the environment to ensure the survival of the device. The main advantages that make wave energy such an important field of investigation is that waves are more predictable than wind, providing a better forecast of the energy production in a day.



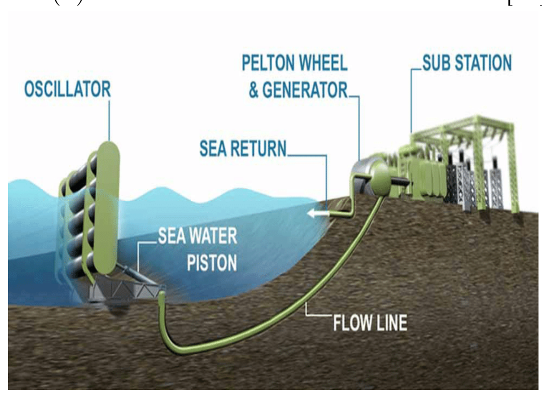
(a) Point absorber. Source: ResearchGate [36].



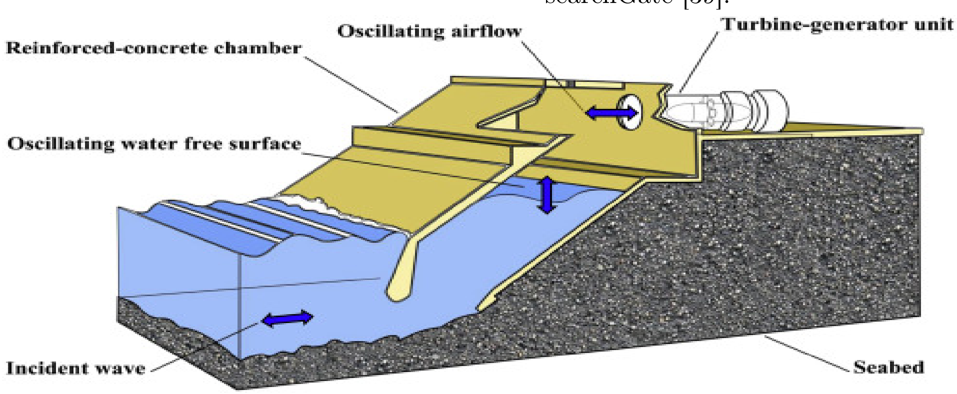
(b) Attenuator. Source: ResearchGate [37].



(c) Overtopping. Source: ResearchGate [38].



(d) Oscillating wave surge convertor. Source: ResearchGate [39].



(e) Oscillating water column. Source: ResearchGate [40].

Figure 4.18: Different types of wave energy converters.

Waves are caused by a number of forces, such as wind, gravitational pull from the sun and moon and other factors such as changes in atmospheric pressure, earthquakes... [32]. Wave energy refers specifically to the wind-caused waves. Considering that oceans cover 71% if the Earth's surface and that wind waves can travel long distances losing little energy, it is possible to assume that the wave power reaches continuously every coastline in the ocean. The total energy flux is defined by:

$$P = \frac{\rho g^2}{64\pi} H^2 T \tag{4.14}$$

Where H is the significant wave height and T is the wave period. This means that, for example, waves with an average height of 3 m and a period of 8 s, have a power of:

$$P = \frac{1 \times 9.81^2}{64\pi} \times 3^2 \times 8 = 34.46 \frac{kW}{m} \tag{4.15}$$

Which implies a relatively low power density for the wave power. As well, equation 4.14 requires to have high waves within long periods of time. There are not many places in the world with potential exploitable wave energy resources, figure 4.19 shows some of them.

Figure 4.19: Exploitable wave energy resources worldwide. Source: Alternative Energy Sources and Their Applications course documents [32].

In order to achieve a competitive status, wave energy must be developed in four aspects [31]:

- Robust and efficient devices.
- Select the areas of interest to install wave farms.
- Decrease the total costs of the wave farms, including installation, maintenance and decommissioning.

- Analyze the impact that wave farms cause in the marine and coastal environments. These impacts could be also beneficial, for example, reducing the wave energy that reaches the coastline.

There are two types of wave resource: offshore and nearshore. For this project, offshore resource will not be explained as it is out of the Port boundaries.

Nearshore waves are waves that interact with the seabed, as near the shore the ocean is not as deep as offshore. When waves reach the shore, they start to 'feel' the seabed. At the moment the wave base touches the seabed, the spatial uniformity of the waves offshore is transformed into spatial variability nearshore [28]. When this happens, the wave resource is concentrated in particular areas caused by the irregularity of the seabed.

4.4 Remaining challenges for marine energy

Both tidal and wave energy resource have many advantages related to the energy production, as they are clean, renewable and almost continuous resources. But they face other disadvantages related with the energy production such as the cost, the connection to the grid and low power density (in the case of wave resource) making the devices quite lengthy. As well, marine energy has to overcome several technological issues in order to make them a profitable and reliable way of producing energy; most of them related with the survival of the devices in the extreme ocean conditions [29].

- **Materials and manufacture.** New materials, as well as new manufacturing processes, must be developed in order to reduce costs and improve the performance of the device with the marine environment. This means, understand the corrosion processes that are being performed in the devices in the sea and use new coatings and techniques to minimize the corrosion effect in the long term, ensuring a longer lifetime for the device.

- **Survivability and reliability.** The survival of the devices in the marine conditions has to be ensured in order to commercialize them. They must resist the extreme weather conditions but also face high mechanical loads during extreme events. So, they have to ensure their correct operation in these events in order to increase their operation range.

- **Identify the suitable areas.** The overall areas in the world where these kind of power plants are suitable to install is limited. An extensive study should be performed of each area in order to harness the resources in an economic and efficient way.

- **Control and monitoring.** In order to keep track of the offshore devices, remote monitoring and control techniques must be implemented, as well as new operation procedures to reach the devices even in extreme conditions so the overall operation time can be maximized. These operations are dangerous due to the variable weather conditions at sea.

- **Infrastructure and grid connection.** Grid connection in the case of offshore power plants represents one of the largest investments as the connections must be done using subsea electric connectors. Also, integrating the energy generated in the power plant is complicated as it varies continuously and there is no infrastructure near the coast where this energy can be managed before entering the network.

5. Data analysis

In this chapter, the data gathered from the weather station at the port will be presented and analyzed, divided in sections referred to each of the alternative energy sources.

5.1 Solar energy

As it was explained in section 4.1, the main parameter that influences the energy produced from solar energy is the solar radiation received in the place.

Table 5.1: Average solar radiation per month and year, measured in W/m^2. Source: Port Authority of Santander.

	January	February	March	April	May	June	July	August	September	October	November	December
2013	-	-	-	-	165.375	192.233	213.032	179.742	137.700	94.742	36.133	52.194
2014	39.548	81.679	115.548	151.241	196.161	229.233	202.355	168.871	155.767	107.355	52.567	36.677
2015	44.806	50.214	90.258	163.167	161.774	176.200	155.290	149.194	100.367	75.452	46.733	38.935
2016	37.097	57.655	98.742	148.300	185.613	181.800	163.613	176.484	130.533	96.419	50.593	52.548
2017	53.355	72.750	102.935	172.833	181.645	152.233	158.032	147.194	121.167	87.323	59.767	38.000
2018	43.419	62.179	109.387	132.000	155.452	158.467	154.161	166.484	132.733	88.516	63.700	43.194
2019	38.581	90.821	129.548	136.900	167.806	169.267	175.258	144.065	130.867	81.161	38.133	43.387
2020	49.387	72.034	-	-	-	-	-	-	-	-	-	-

It is possible to see that the average solar radiation is not really high for half of the year (October - March), this means that the solar radiation is below 120 W/m^2. Above this value, it is considered that there would be a significant amount of solar radiation, allowing a better performance of the solar cells. Looking back at figure 4.4, it is possible to assume that the best working conditions for the solar cell to work would be with a solar radiation of around 400 W/m^2, which is far from the values obtained even in the summer months. Such is so that, observing more precise measurements of daily solar radiation, from where table 5.1 has been obtained, it is possible to notice that there are few days in the years range between 2013 - 2020 when solar radiation is higher than 200 W/m^2. In total, there are 415 days, from a total of 2496 days of measurements, when the average solar radiation is above 200 W/m^2; which means that less than 17% of the days in a year have higher solar radiation values than 200 W/m^2. Considering that this value is being taken as the minimum value for a photovoltaic solar cell to work properly, it is possible to assume that solar energy will produce a small amount of energy during the year at the port area.

5.2 Wind energy

For analyzing the power potential of wind energy in the area, two parameters have been measured according to section 4.2.2: wind direction (table 5.2) and wind speed (table 5.2).

Table 5.2: Dominant wind direction per month and year in Santander, measured in degrees. Source: Port Authority of Santander.

	January	February	March	April	May	June	July	August	September	October	November	December
2013	-	-	-	-	254.121	181.497	173.852	170.052	194.280	179.352	210.180	186.239
2014	221.587	239.164	235.174	180.731	216.510	203.400	204.481	147.739	133.413	158.226	207.590	234.887
2015	237.484	176.204	194.810	151.580	194.600	164.893	174.703	173.910	169.393	181.142	214.217	202.555
2016	233.597	259.786	192.916	189.273	152.135	170.117	120.268	154.858	134.440	91.374	158.744	182.087
2017	185.406	182.068	188.219	170.650	178.452	205.087	201.794	148.310	234.313	159.819	198.650	216.052
2018	256.171	205.350	206.845	173.747	196.658	220.803	193.339	189.806	165.953	186.365	185.377	183.061
2019	209.987	179.793	208.394	192.200	180.929	210.067	179.406	135.542	192.533	230.542	244.473	193.484
2020	174.768	223.510	-	-	-	-	-	-	-	-	-	-

Table 5.3: Average wind speed per month and year in Santander, measured in m/s. Source: Port Authority of Santander.

	January	February	March	April	May	June	July	August	September	October	November	December
2013	-	-	-	-	3.829	2.497	1.981	2.103	2.050	2.752	3.660	3.229
2014	4.971	5.689	3.513	2.921	2.945	2.650	2.481	2.010	2.030	1.913	3.120	2.635
2015	2.906	3.350	2.113	2.477	2.648	1.953	2.297	2.597	2.553	2.768	2.290	3.110
2016	3.152	3.738	3.503	3.173	7.500	3.297	2.765	2.200	2.470	2.152	2.278	1.471
2017	2.629	2.611	2.123	2.393	2.584	2.450	1.929	1.706	1.743	1.410	1.427	2.497
2018	2.606	2.479	4.213	2.547	3.045	3.823	4.874	3.755	3.330	4.381	4.620	3.790
2019	4.423	5.954	3.068	2.883	3.648	3.090	3.294	2.739	2.827	2.968	4.807	5.068
2020	3.590	3.007	-	-	-	-	-	-	-	-	-	-

First of all, focusing on table 5.2 and considering that the wind directions are:

- North: 0 degrees.
- East: 90 degrees.
- South: 180 degrees.
- West: 270 degrees.

Analyzing the dominant directions, it is obtained that winds from the south-west direction are the dominant winds during the year, followed by the north-east direction. There are also some months where the south-east direction is dominant but are relatively few compared with the other directions.

In the case of wind speed, the average wind speed per month is around 3 m/s, which is about 10.8 km/h. It is not a high mean wind speed but, analyzing the data used for creating table 5.2 which contained the mean values of wind speed per hour, it is possible to see that there are also winds faster than that value. Furthermore, wind roses for every month and year between 2013 and 2020 were created with data gathered every 10 minutes between those years. These wind roses are shown in appendix .1 and were created using a MATLAB function created by the Spanish Institute of Oceanography, shown in appendix .2 [41]. These figures corroborate that the dominant wind directions (south-west and north-east) are also the directions from where the strongest winds come. Figure 5.1 summarizes all the measures taken to make the figures in appendix .1 in one same wind rose.

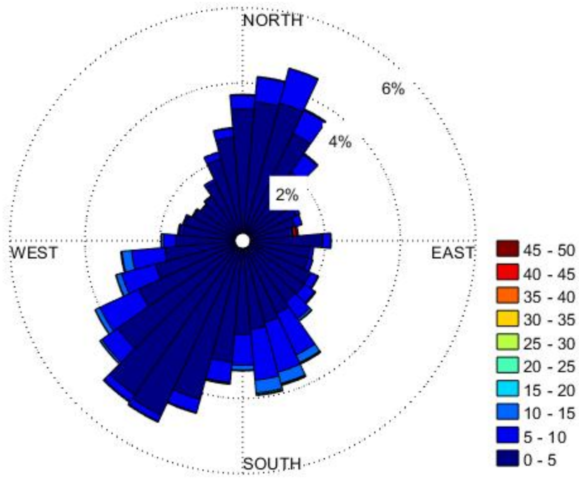


Figure 5.1: Wind rose for the Santander's port summarizing the winds between 2013 - 2020. Source: Port Authority of Santander.

Once again, this figure shows that, indeed, the south-west and north-east wind directions have been the prevalent for the last 7 years. It is possible to notice, also, that the wind speed is not very fast, this is because the moments when the wind is faster last for some minutes only, maybe hours, so compared with the total amount of minutes in 7 years this measures are almost imperceptible in the diagram.

With this mean wind speed value, bringing back equation 4.10 and considering a general wind turbine of 63 m of radius (around 3.5 MW of power [42]); it is possible to calculate that the maximum wind power extracted with one turbine would be around 95.3 kW. This value means that the average total energy produced by this wind turbine in one year would be 834.8 MWh, considering that the power output is constant throughout the year. Even though, if this calculation is made, for example, with every value obtained per 10 minutes for the year 2019, it is obtained that the total energy produced would be around 3470.8 MWh per turbine, which is significantly higher. Considering that the wind turbines start to produce energy when the wind speed is equal to 3 m/s, having a mean wind speed of this value implies that the wind turbines would be producing energy most of the year, reaching the highest values when the wind speed reaches 13 - 14 m/s. These wind speed values are also reached sometimes, but only represent the 2% of the total values gathered in 2019. But, on the other hand, the wind turbine will stop producing energy because of security concerns when the wind speed is faster than 25 m/s. The total energy calculation made before considered both these conditions, minimum and maximum air speed.

5.3 Marine power

5.3.1 Tidal energy

For studying the tidal energy resource, a compilation of tide tables from 2010 to 2020 for Santander has been done. These tables, have been analyzed in order to obtain the mean tidal ranges for the place. In table 1 at appendix .3, an example of the analysis done is shown for the year 2019. Note that the moon phase is also recorded in the table as: LL (full moon), N (new moon), C (crescent moon), M (waning moon).

The mean tidal range value for 2019 is 2.79 m, which includes values from 1 meter of tidal range to almost 5 meters (mesotidal). Also, looking at Santander's geography in figure 2.1b, it is possible to see that the port is located in a bay, which is a semi-enclosed body of water indeed. This would make it possible to install a tidal barrage or a tidal lagoon in order to produce energy from the tidal resource. However, the total energy that could be produced through this method could not be very high. Referring back to table 4.3 in section 4.3.1, it is possible to see that an average value of 2.79 m is not comparable to the average values of the suitable locations, which are mostly above 5 meters. This means that the possible tidal power plant that could be installed in Santander would produce less than La Rance, which has an average power of 240 MW. This values will be further discussed in the discussion section. According to equation 4.13, and considering that the Bay of Santander has an area of 22,420,000 m^2, with a turbine efficiency of 40%; the capacity of the tidal power plant would be:

$$P = \frac{0.4 \times 9.81 \times 1 \times 22420000 \times 2.79^2}{12.5 \times 3600} = 15.2MW \tag{5.1}$$

5.3.2 Wave energy

The analysis of the wave resource is made with data gathered from the government agency Ports of Spain, which is a division of the Transport, Mobility and Urban Agenda Ministry of

Spain [43].

Figure 5.2: Location of the buoy where the data was measured. Source: Ports of Spain [43].

The data is presented as a wave rose, which shows the wave height and direction parameters, as well as the frequency of repetition (the bigger the bar, the more waves in that parameter). Figure 25 in appendix .4 shows the summarized data for the range of years between 2010 and 2020.

It is noticeable that the average wave height is contained between 0.2 m and 2 m, which would not produce a great amount of energy when compared with the example in equation 4.15. Figure 5.4 shows even clearer the prevalence of 0.5 - 1 meter waves above any other height, and figure 5.3 represents the wave height in relation with the period:

Tabla Hs vs Tp / *Hs vs Tp Table*
SIMAR 3138035

EFICACIA: 94.14% AÑO/YEAR: 2010-2020		Tp (s)											
		<=1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	>10.0	TOTAL
Hs (m)	<=0.5	---	---	0.032	0.355	1.842	2.427	1.237	1.667	2.330	3.652	8.965	22.505
	1.0	---	---	0.001	0.095	0.690	2.909	3.386	2.514	2.784	4.493	27.800	44.671
	1.5	---	---	---	0.002	0.004	0.087	0.525	1.382	0.927	0.945	15.154	19.028
	2.0	---	---	---	---	---	0.003	0.018	0.205	0.445	0.426	7.117	8.214
	2.5	---	---	---	---	---	---	0.001	0.014	0.084	0.207	3.063	3.369
	3.0	---	---	---	---	---	---	---	0.001	0.008	0.047	1.226	1.282
	3.5	---	---	---	---	---	---	---	---	---	0.001	0.563	0.564
	4.0	---	---	---	---	---	---	---	---	---	---	0.252	0.252
	4.5	---	---	---	---	---	---	---	---	---	---	0.077	0.077
	5.0	---	---	---	---	---	---	---	---	---	---	0.030	0.030
	> 5.0	---	---	---	---	---	---	---	---	---	---	0.009	0.009
	TOTAL	---	---	0.033	0.452	2.536	5.426	5.167	5.783	6.578	9.772	64.254	100%

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Figure 5.3: Wave height - period table for the Santander's port between 2010 - 2020. Source: Ports of Spain [43].

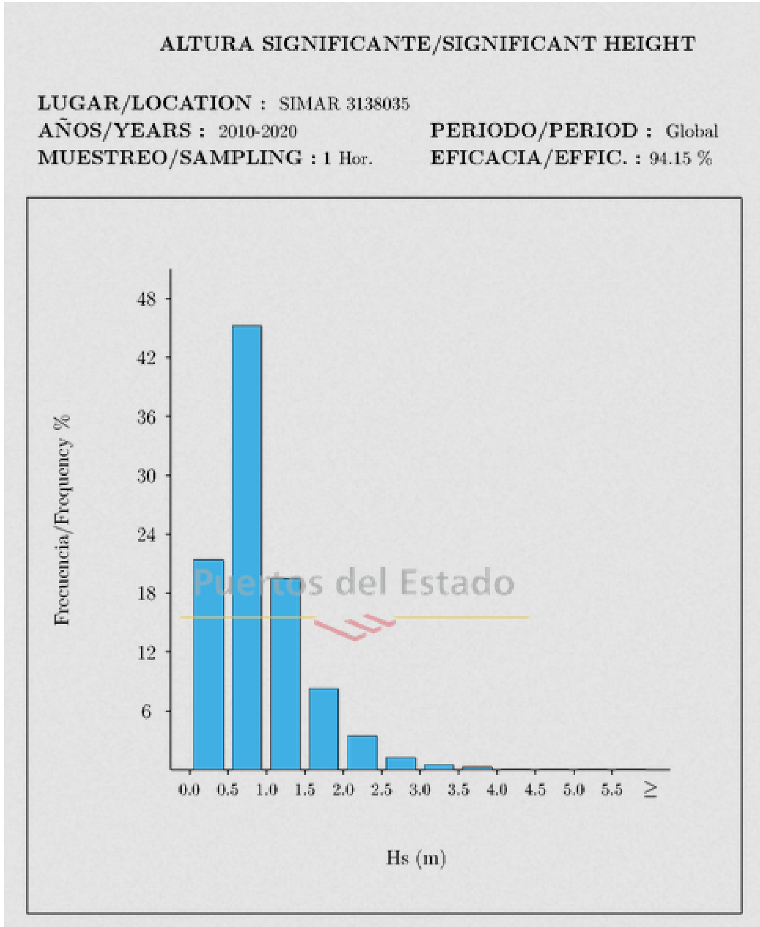

Figure 5.4: Wave histogram for the Santander's port summarizing the wave height and frequency between 2010 - 2020. Source: Ports of Spain [43].

Based on this data, and returning again to equation 4.15, it is possible to calculate the average power per meter for this energy resource, taking 1 m as the mean height value and a period greater than 10 seconds (for example 12 seconds) as seen in figure 5.3:

$$P = \frac{1 \times 9.81^2}{64\pi} \times 1^2 \times 12 = 5.74\frac{kW}{m} \tag{5.2}$$

Which is a lower power density value compared with equation 4.15, that already had a low value. This means that a wave power plant would need to have a length of kilometres in order to produce a substantial amount of energy.

6. Discussion

With the data from each of the alternatives gathered and analyzed, in this chapter they will be compared, pointing out the advantages and disadvantages of each of them. Some discussion has been already made in the data analysis section, regarding mainly the forecasted energy production compared with the already existent examples treated in chapter 4.4. This chapter will focus mainly in what differences make one of the alternatives more suitable attending to the energy produced, the area occupied/where to be placed, connection to the electrical grid... Among other subjects. As the energy produced in all cases depends on the area occupied, this will be the first subject addressed.

6.1 Area occupied and possible energy production

The total area occupied by each of the power plants will directly affect the total energy output they produce: the greater the area, the larger the power output. Considering all the results obtained, it stands to reason that the solar power and the wave power plants would take the greatest areas of land, due to their low power density. It was said in section 4.1 that a solar plant of 1 GW of capacity could take up to 25 km^2 in a place with relatively high solar radiation. For the case of wave energy, it has been calculated in section 5.3.2 that the power per meter in Santander is about 5.74 kW/m, which means that it could produce 1 GW of power in almost 200 km.

Both of these alternatives have a really low power density and, focusing on solar energy, the Port of Santander has a relatively small area (3 km^2 [44]) for the possible emplacement of the power plant. This means that if the whole area of the port was covered with solar panels, it would have a capacity of around 120 MW of power, doing a simple rule of three. One alternative would be placing the solar panels in the roofs of each of the buildings but, assuming that huge parts of the port are destined for car-shipping parking, it is possible to consider that the buildings only represent less than 20% of the area. Doing again a rule of three, it would mean that the achieved capacity using the roof area would be 24 MW.

In the case of the tidal power plant, it was calculated in the data analysis chapter that the average power would be of 15.2 MW. It is of course a very low value compared with the other alternatives already analyzed but it has also another problem. The Port of Santander is located inside the bay, so a tidal barrage would mean that the ships would be unable to enter the bay. As one of the limitations of this project work (set in chapter 3) was to not interfere with the normal operation of the port, this alternative will be discarded because of this reason. Other choice would be building a tidal lagoon although, looking at the small power output for the whole bay with a tidal barrage, it is easy to assume that the power output given by the tidal lagoon would be even lower. So, because of these reasons, tidal power generation will not be addressed further in this discussion as it is unsuitable for this location.

Finally, attending to wind energy, the amount of energy produced depends on the type of turbines chosen for the project. It will be considered for this case that 3.5 MW turbines will be used, with a diameter of 126 m [42], as it was said in the data analysis section. The construction of the wind farm could be done onshore or offshore, but it has been previously stated that the area of the port inland is quite reduced and occupied almost in its totality. So that, an offshore wind farm could be a better option for this alternative. Figure 6.1 shows two possible locations for an offshore wind farm. The lower one is a shallow area in the bay, no more than 5 metres deep during high tides [44], of around 2.25 km^2 (a square of 1.5 km on each side). The upper area is deeper, but on the other hand has much more space, so the wind farm could be as big as the investment could be.

Figure 6.1: Satellite image of the Bay of Santander with two possible offshore locations for the wind farm. Source: Google Maps.

Furthermore, referring to chapter 4.4, the wind turbines installed will have to maintain a certain distance in order to avoid interference in the wind flow between them. Considering the installation of 3.5 MW wind turbines, the distance between turbines should be around 1260 m parallel to the wind flow and 378 m perpendicular to the wind flow. With these parameters, it would be possible to install two lines of 4 wind turbines in the lower area of figure 6.1, making a total of 8 wind turbines with a total capacity of 28 MW facing the south-west direction. These turbines, according to what was presented in section 5.2, could have produced a total of 3500 MWh of energy per turbine for the year 2019. Multiplying this value by the total number of turbines it is obtained a possible energy production of 28 GWh per year.

The construction of the wind farm in the emplacement shown in the upper part of figure 6.1 would be harder to accomplish, as in this area the water is deeper than near the shore. Contrarily, this place could contain a larger wind farm than the area shown before as there is more space. So that, the size of the power plant could be as large as the investment allows it.

Summarizing, wind energy would be the best alternative in terms of energy production, followed by solar energy and wave energy. Also, it has the advantage of flexibility regarding the emplacement of the power plant, while solar energy has the problem of the lack of space within the port area inland, maybe being reduced to scattered solar cells among the roofs of the buildings, and wave energy should occupy large areas of water in order to produce a substantial amount of energy due to the low energy density.

6.2 Connection to the electrical grid

Each of the alternatives will be connected differently to the electrical grid. As for the case of the offshore wind energy and wave energy, this connection will be done using underwater cables while, for the solar energy, it will be easier to connect to the grid. Even, if the solar panels are finally located on the roofs, it might be not necessary to connect them to the grid, and use the energy produced by them directly in the building they are located.

The underwater connection using cables is one of the main costs of every offshore power plant, getting more expensive the further the plant is from the shore. Comparing the two alternatives that would need this kind of connection, wind energy would need a shorter cable length, as it would be located nearer to the shore than the wave power plant, that would be located in the open sea (in the upper part of figure 6.1) in order to get higher waves. Instead, the wind farm would have a shorter cable connection for then switching to a normal overhead transmission line.

6.3 Other concerns

Setting aside the technological and infrastructure concerns, there are other issues that need to be considered. One of them is the social impact. Each of the alternatives would have both positive and negative social impacts. The common positive impact for all of them is the creation of new jobs related to the construction and maintenance of the power plant. Also, in the case of the wave energy power plant, it would be used as a research instrument that would help in the development of wave energy technologies.

On the other hand, these alternative energy sources have their downsides. Solar energy would be the alternative with the less social impact, as installing solar cells in the roofs would almost not affect anyone living near the port. But, wind energy would create great confrontations. The wind farm has the greatest visual impact of the three alternatives, it would be located right in the middle of the bay or in the ocean so they would be visible to anyone in the shoreline. Some people in the city could think that the wind farm damages the landscape of the shore of Santander and, consequently, would disencourage the construction of it, stating that it would have a negative impact in sectors such as tourism. The same happens with the wave energy power plant, but to a lesser extent. Wave power devices are not that visible, as normally they only rise a few meters above the water, but are also appreciable from the shore. Also, wave energy has another issue added in comparison to the offshore wind farm. As the wave energy converter would be located in deep water, this area will not be suitable for boat navigation. This would not happen with the wind farm, as it would be located in a shallow place in the sea, where it is impossible to navigate because of the risk of ships grounding.

At the same time, solar energy would have one main problem regarding its installation. Not all the buildings in the port belong to the Port Authority, so that, each of the owners of every building that belongs to another company should be contacted and convinced about the initiative. Besides, depending on the building, it might be impossible to install the solar cells on its roof, which would decrease the total power installed. Even if the panels were installed, the consumption would be made by the external company in that building, so the port would not get any benefit from the investment so, in the end, it would make no sense to install the solar cells on these roofs.

7. Conclusion

By pooling all the ideas mentioned during the last chapters, there are several reasons to choose each of the alternatives or not. After discarding tidal power due to its incompatibility with the project requirement of not interfering with the port activity (established in the method chapter); only three alternatives are left: wind energy, solar energy and wave energy. From all the parameters studied and the forecasted performance, wind energy seems the best option for the Port of Santander. This decision could change based on legal concerns and other issues that may appear in further development stages of the project but, from a theoretical point of view and taking into account the shown variables, it would be the best choice for several reasons.

First of all, it is the option that provides the highest energy generation among all of the possibilities. Solar energy provides a better flexibility in terms of where to place the solar cells, but it has been proven that the total area that could be covered with them would be relatively small, which would lead to a low energy generation. Wave energy in this case has the lower power density, meaning that a huge area of sea should be covered for obtaining a reasonable energy production.

Furthermore, regarding the parameters for an optimal energy production for each type, it was seen that both solar energy and wave energy had low values for their resource's parameters. This means that solar radiation was relatively low in the case of solar power and wave height was also low in the case of wave energy. But, in the case of wind power, it had better values compared to the other two: the average wind speed was equal to the minimum required for wind power generation and, most of the time, the strongest winds blow from a dominant direction. This makes the installation of a wind farm more suitable than any of the two other choices.

Besides, wind power is the most developed technology from the three alternatives. Solar energy still needs further research in order to achieve better efficiencies of energy conversion and wave energy is in the first steps of its development, so a full scale prototype would probably cause several problems during its operation regarding malfunctions or any other faults. On the contrary, wind energy achieves better efficiencies than both of the other two alternatives, since it has been in development for much longer. This means that its operation will be more reliable in terms of faults that may occur, so for most of the time only routine maintenance will be necessary to minimize these possible faults.

The location of the power plant would be greatly discussed, as the option inside the bay would be easier to accomplish, but it would have less capacity than the location outside of the bay, which on the other hand would be more expensive but would have much more space for the construction. Depending on the investment made, the viability of one of the alternatives could be more suitable than the other. A high investment could result in the possibility of creating a bigger wind farm, with more capacity. Thus, this plant would need more space for installing more turbines, so it would have to be built outside of the bay. Otherwise, a lower investment would be better exploited in the construction of a smaller plant, with less capacity, but nearer to the shore for a better connection to the electrical grid that would reduce the overall costs. This reduction in costs regarding the connection could result in a higher investment in the wind turbines.

One of the main issues with this decision would be the social concerns, as many people in the city will not like the final location of the wind farm, justifying that it damages the landscape of the Bay of Santander. This could cause several discussions between the port and the city of Santander before the construction of the wind farm, promoting several campaigns showing the benefits that a wind farm could provide in terms of green-energy production and creating digital models that simulate how would the landscape look like after the construction of the wind farm, so people could have a better understanding on which area would be covered by the turbines. These campaigns could change the thought of many people and make them look favorably to the construction of the wind power plant.

Another possibility would be adding solar cells in the roofs of some of the buildings property of the Port Authority, to work in combination with the wind power plant. This is stated just to clarify that it is possible to combine different solutions instead of just choosing one of them and discard the others directly. This combination would reduce even more the use of non-renewable energy sources for the production of the energy consumed in the port what, in the end, would make a small contribution to the global problem with greenhouse gasses emissions and climate change. The same happens with wave energy, building a wave farm would have two main benefits: it would produce some more energy from renewable sources and it would help in the research of more efficient wave energy conversion devices. The goal of this project was to choose one of the proposed alternatives, and wind energy has been the selected one. But, this does not exclude the possibility that, in the near future, more renewable energy production alternatives could be implemented in the port, making its energy consumption less polluting for the environment.

Summing up, this project's aim was to develop a preliminary research in order to choose which renewable energy source was the most suitable for the area of the Port of Santander. The renewable energy sources researched have been four: solar energy, wind energy, tidal power and wave power. After all the research carried from each technology and the analysis of the data gathered from the weather stations, it was concluded that wind energy would be the best option for renewable energy production in the port. The construction and specifications of the wind farm would require further development rather than what has been done in this project but, from a general point of view and as a preliminary study, wind energy would contribute in the goal of reducing the external energy consumption in the port and start consuming energy from green sources produced within the boundaries of the port itself. This change in the energy consumption will also help indirectly with the threats that the whole world is facing nowadays, as stated in chapter 1. As climate change is becoming one of the main issues of the century, every possible contribution to try to stop it and reverse it is necessary, even in a rather small scale like in this case. This case, on its own, may not make a great contribution to the global problem but, a combination of many small cases like this one can make a real difference. This change of mentality regarding the traditional ways of producing energy is key if the world wants to stop this global issue.

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List of Figures

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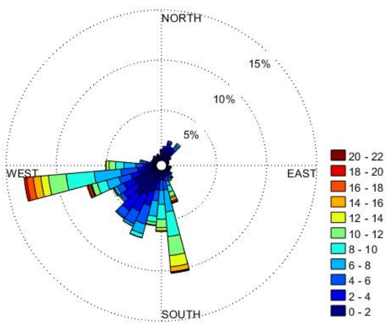
Appendix

.1 Wind roses

This appendix contains the wind roses per month of the years 2013 - 2020. The data used for creating these wind roses was measured every 10 minutes.

.1.1 January



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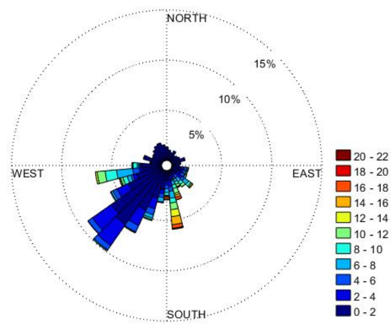

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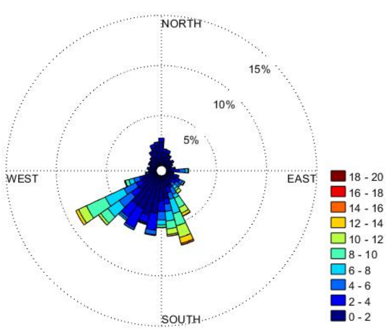

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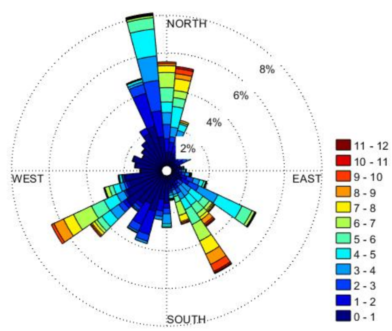

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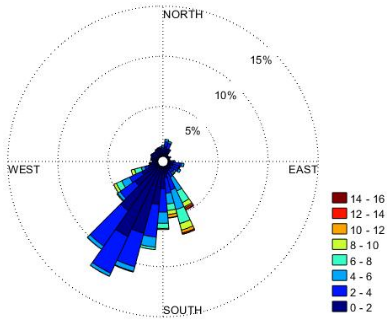

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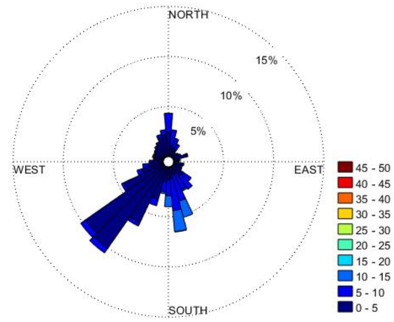

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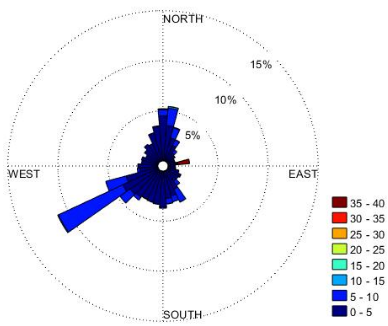

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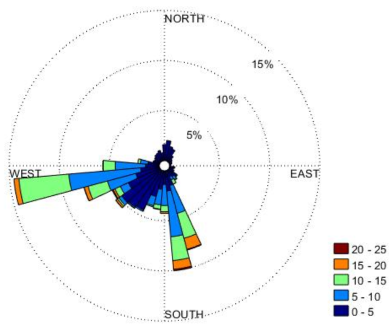

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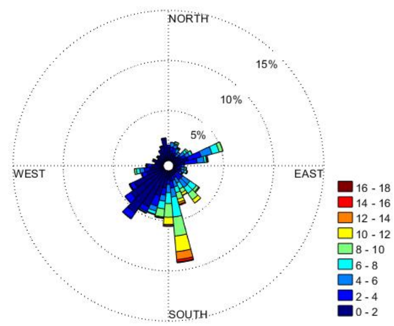

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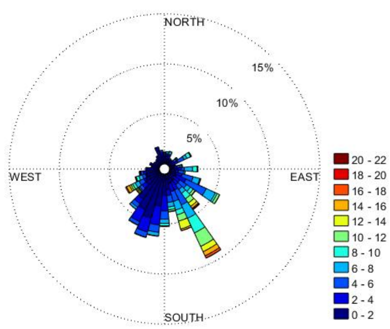

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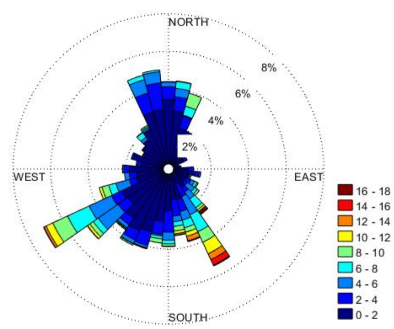

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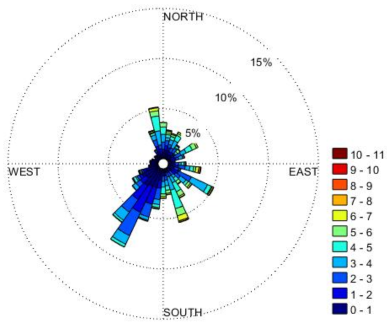

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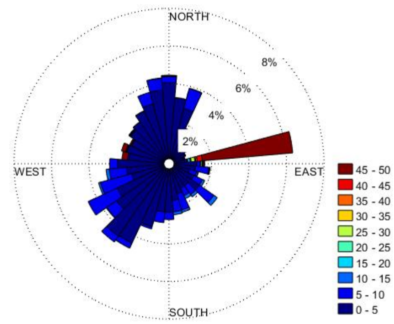

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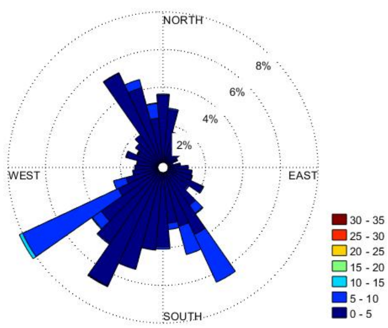

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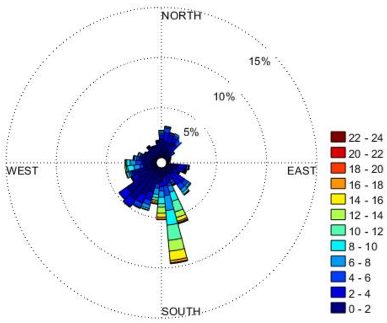

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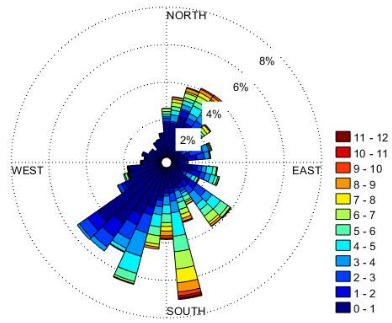

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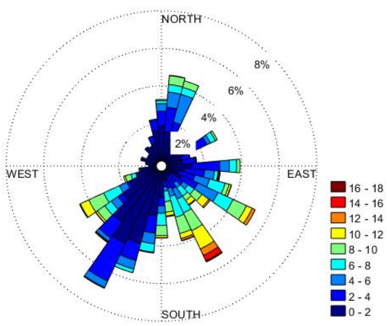

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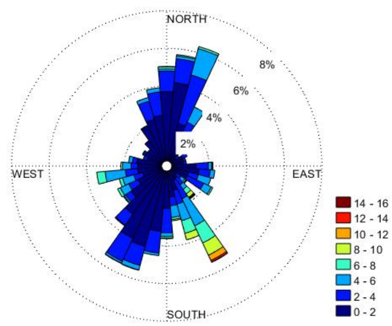

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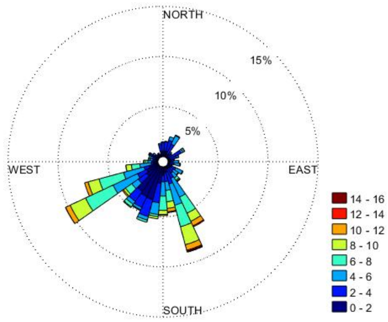

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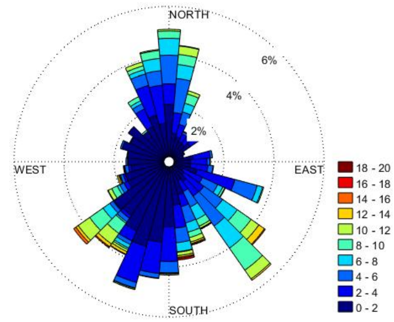

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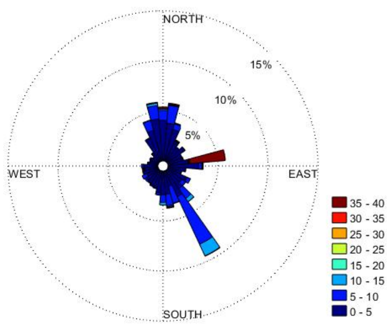
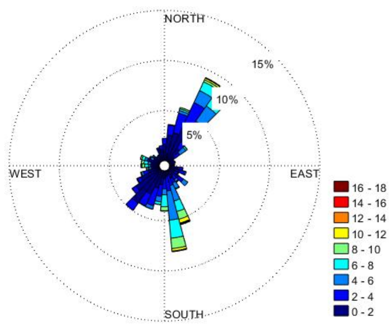
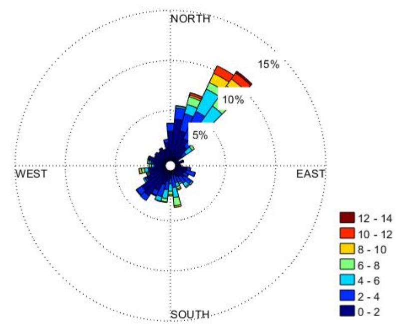


March 2020.

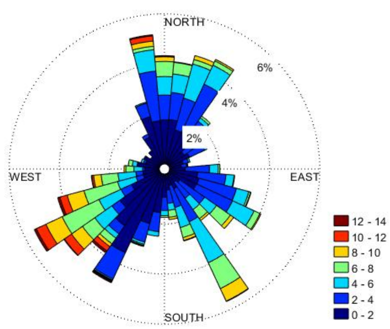
.1.4 April



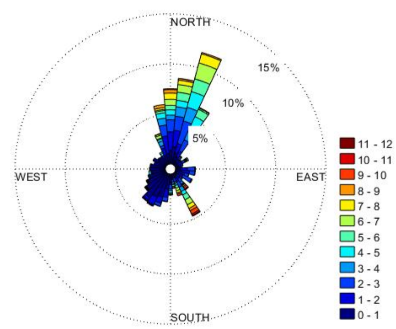
April 2014.



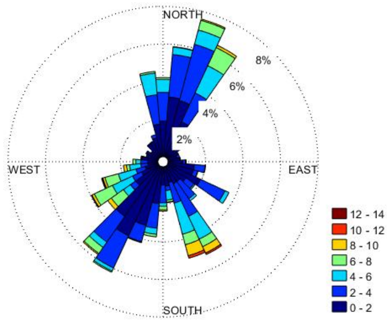
April 2015.



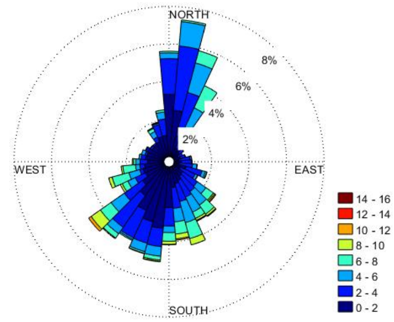
April 2016.



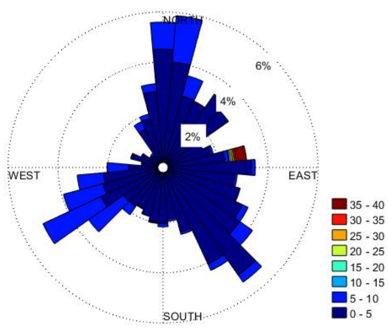
April 2017.



April 2018.

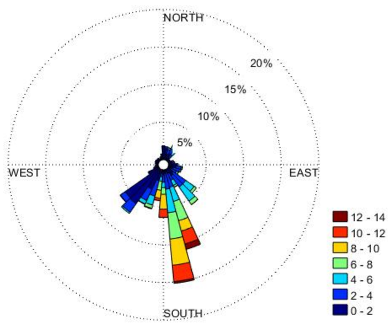


April 2019.

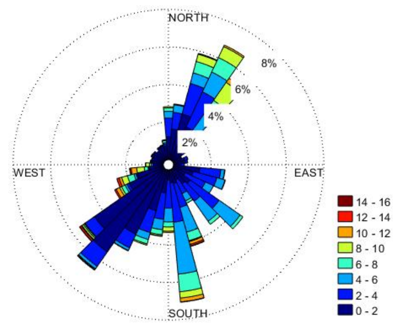


April 2020.

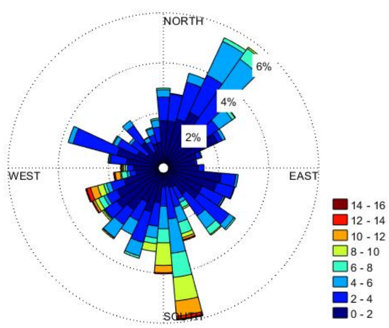
.1.5 May



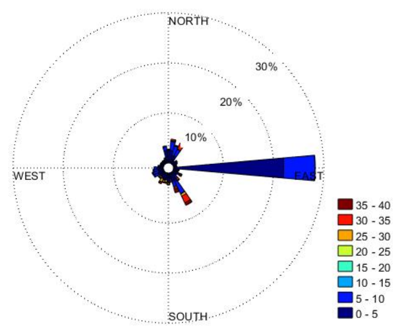
May 2013.



May 2014.



May 2015.



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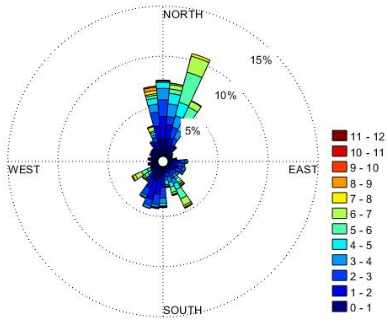
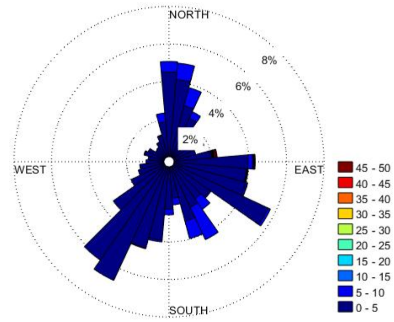
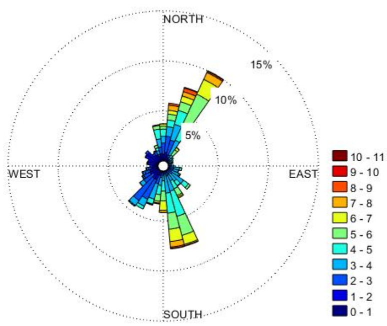


May 2017.

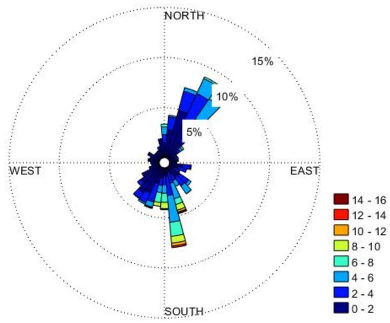


May 2018.

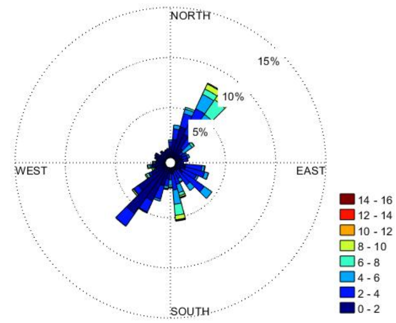


May 2019.

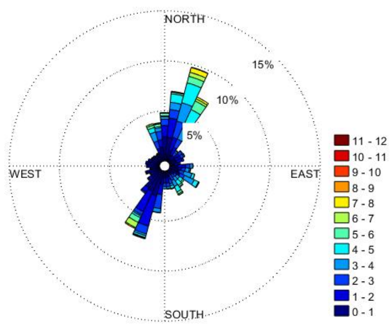
.1.6 June



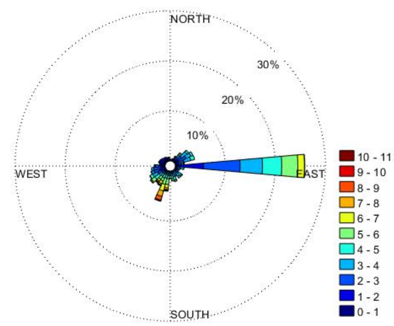
June 2013.



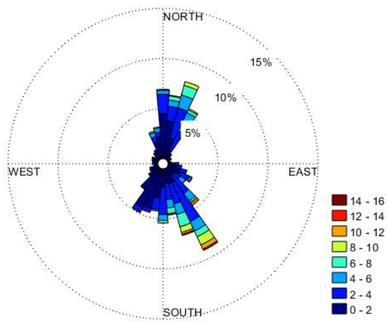
June 2014.



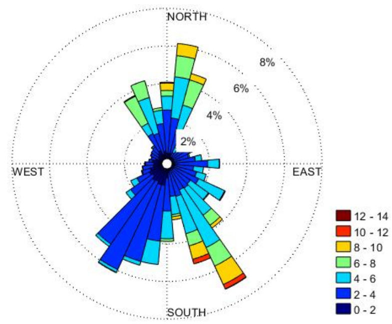
June 2015.



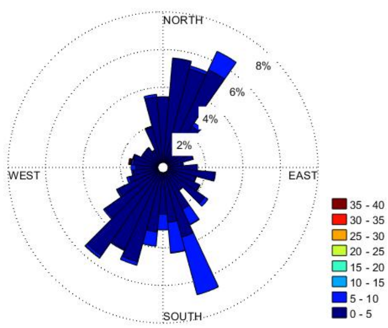
June 2016.



June 2017.

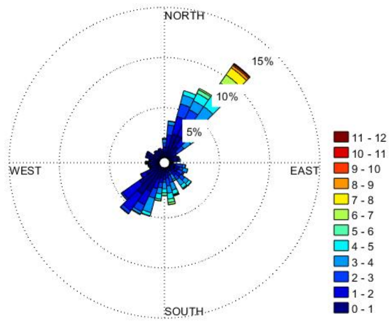


June 2018.

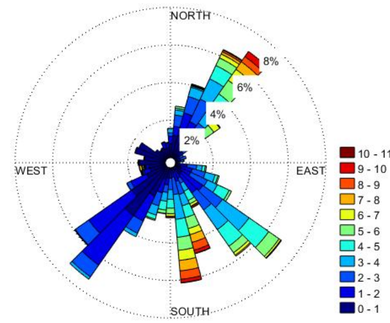


June 2019.

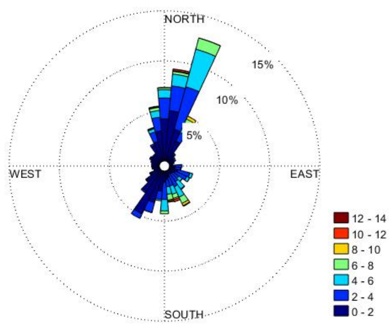
.1.7 July



July 2013.



July 2014.



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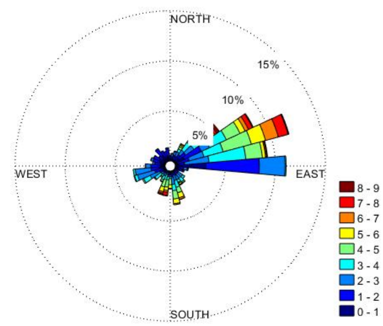

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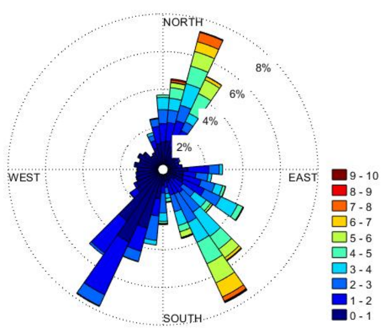

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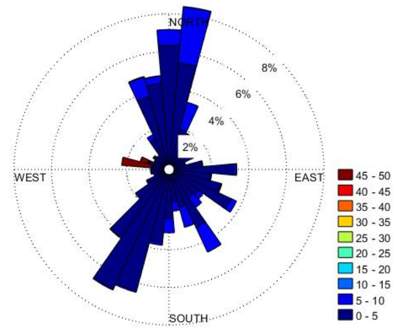

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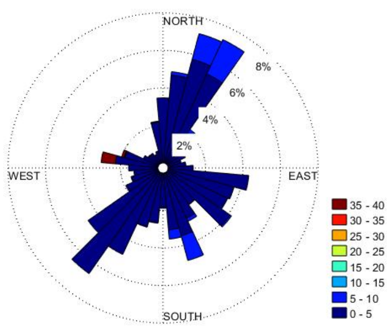
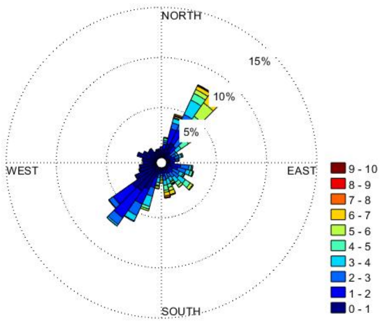
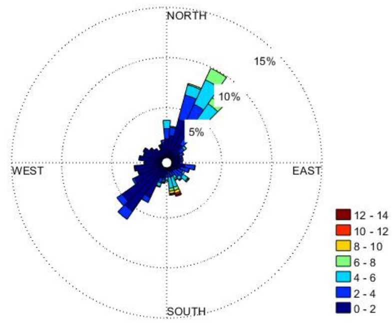


July 2019.

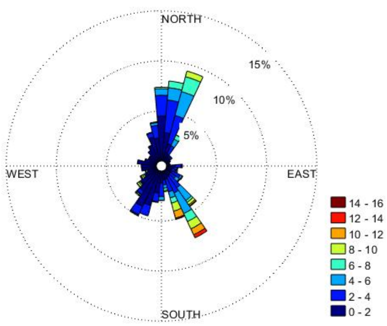
.1.8 August



August 2013.



August 2014.



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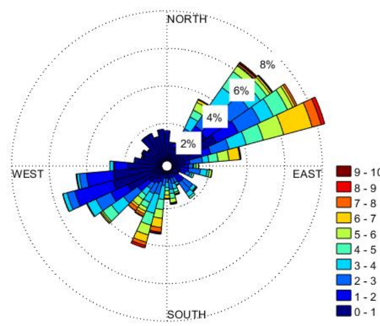

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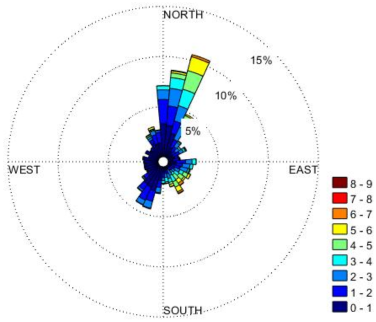

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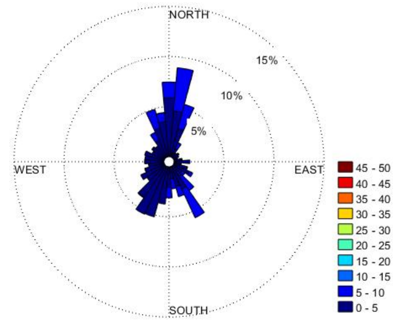

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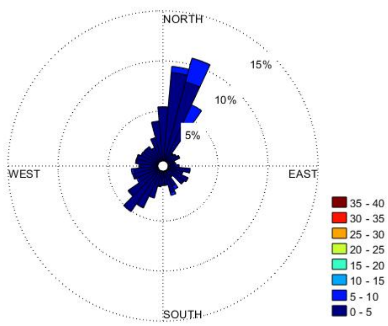
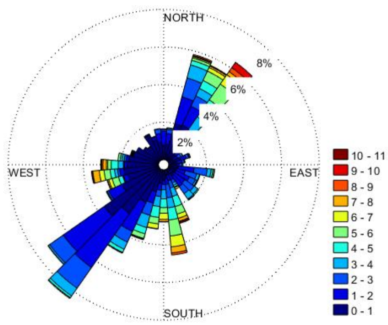
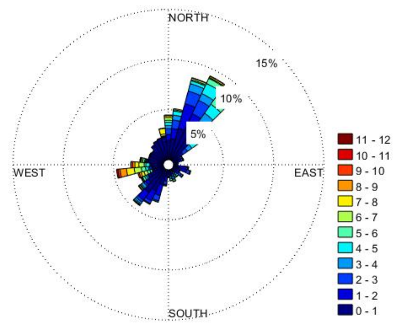


August 2019.

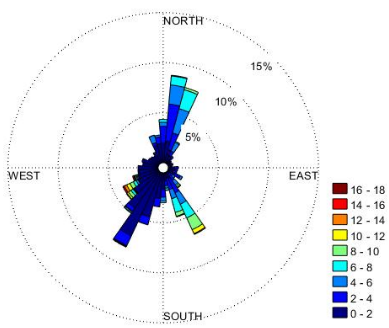
.1.9 September



September 2013.



September 2014.



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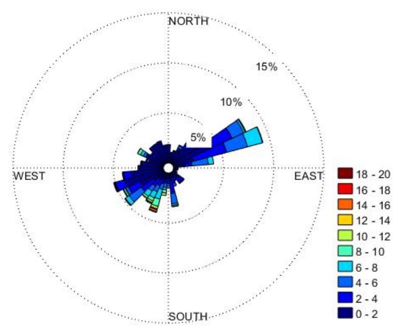

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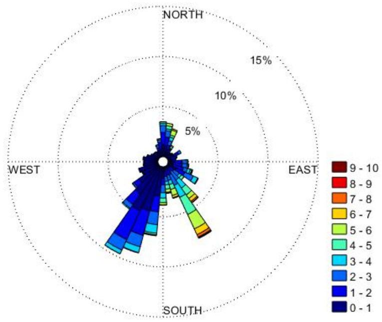

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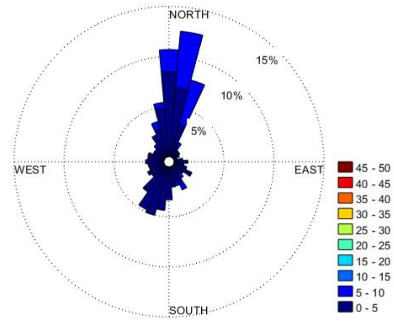

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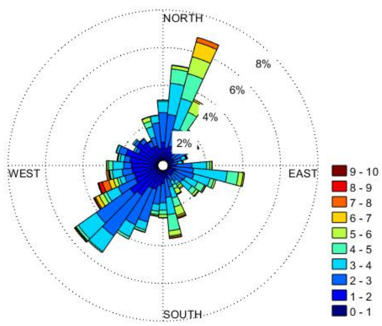
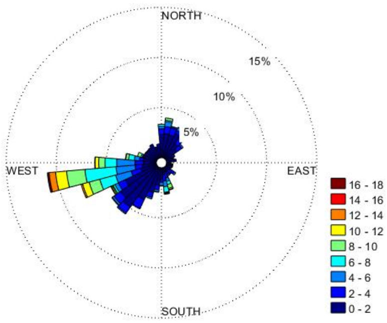
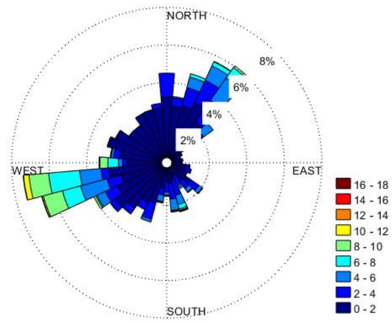


September 2019.

.1.10 October



October 2013.



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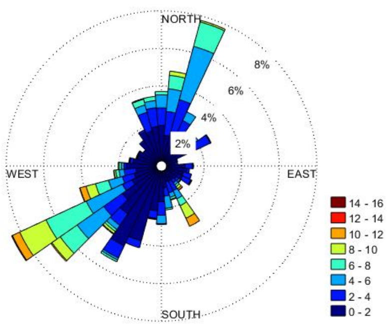

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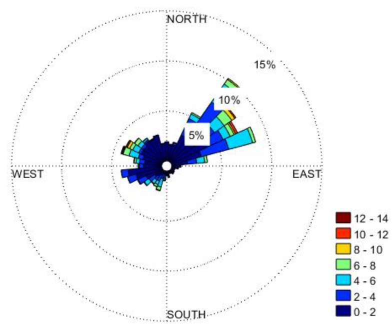

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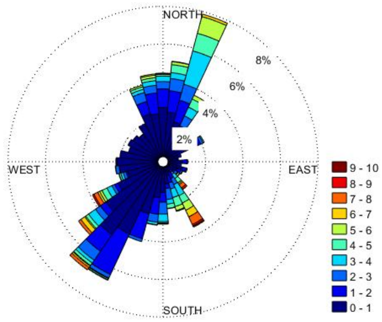

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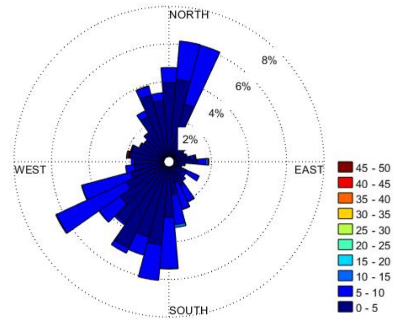

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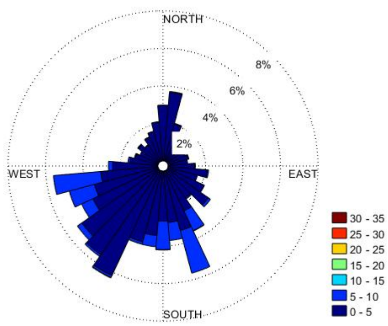
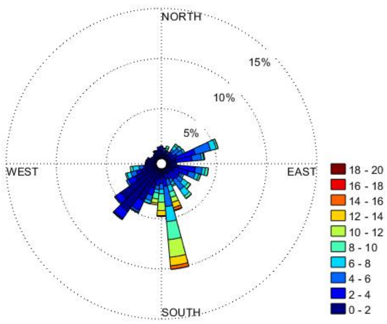
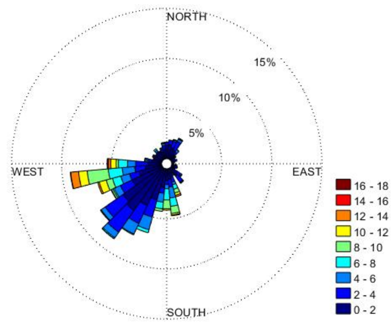


October 2019.

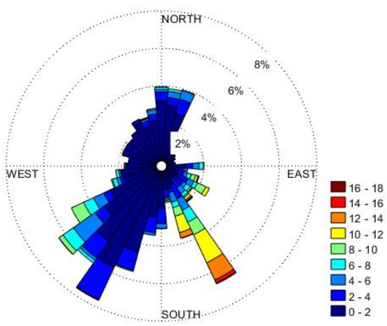
.1.11 November



November 2013.



November 2014.



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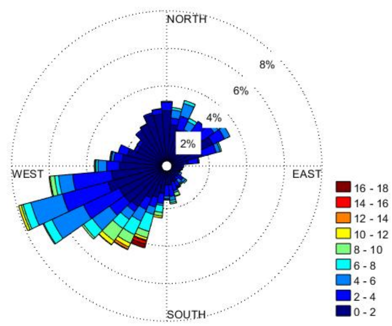

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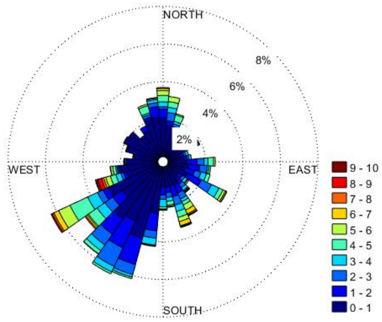

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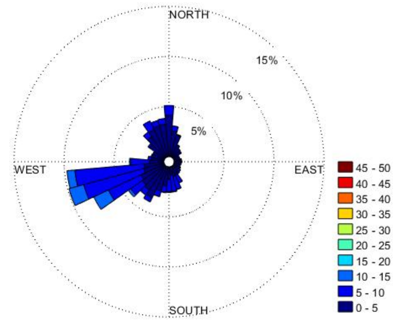

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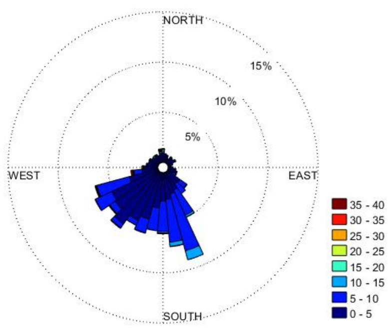
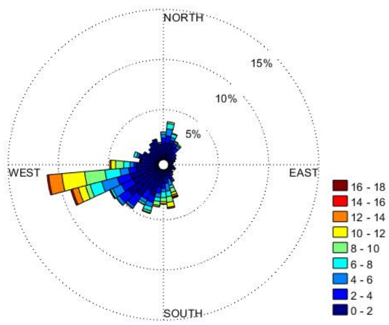
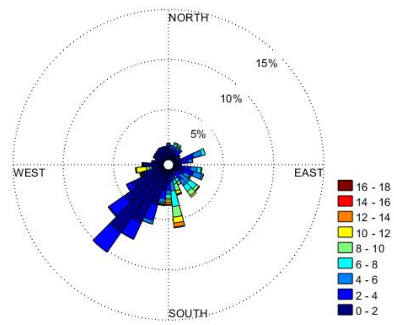


November 2019.

.1.12 December



December 2013.



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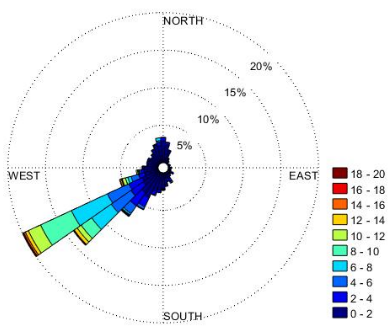
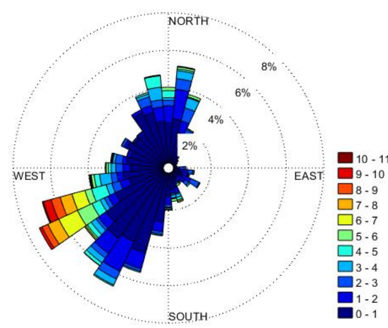
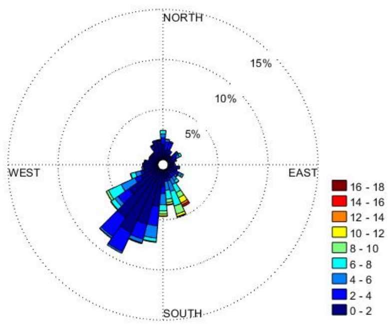


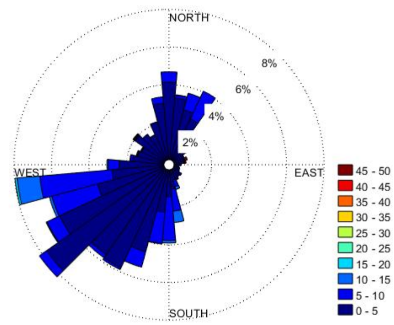
December 2015.



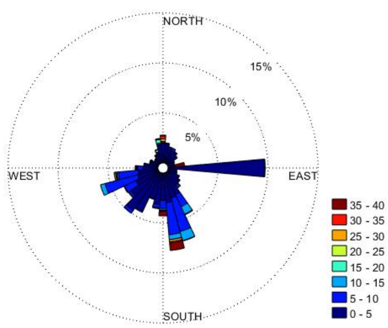
December 2016.



December 2017.



December 2018.



December 2019.

.2 MATLAB code used for creating wind roses from an excel file

```
function varargout = wind_rose(D,F,varargin)
%WIND_ROSE   Wind rose of direction and ...
    intensity
%
%   Syntax:
%      [HANDLES,DATA] = WIND_ROSE(D,I,VARARGIN)
%
%   Inputs:
%      D   Directions
%      I   Intensities
%      VARARGIN:
%       -dtype, type of input directions D, ...
    standard or meteo,
%             if meteo, the conversion ...
    dnew=mod(-90-D,360) is done;
%             if not meteo, standard is used ...
    (default)
%       -n, number of D subdivisons
%       -di, intensities subdivisons, ...
    default is automatic
%       -ci, percentage circles to draw, ...
    default is automatic
%       -labtitle, main title
%       -lablegend, legend title
%       -cmap, colormap [jet]
%       -colors, to use instead of ...
    colormap, for each di
%       -quad, Quadrant to show percentages [1]
%       -ri, empty internal radius, ...
    relative to size of higher
%             percentage [1/30]
%       -legtype, legend type: 1, ...
    continuous, 2, separated boxes [2]
%       -bcolor, full rectangle border ...
    color ['none']
%       -lcolor, line colors for axes and ...
    circles ['k']
%       -percbg, percentage labels bg ['w']
%       -ax, to place wind rose on pervious ...
    axes, the input for ax
%             must be [theax x y width], ...
    where theax is the previous
%             axes, x and y are the location ...
    and width is the wind
%             rose width relative to theax ...
    width (default=1/5)
%       -parent, by default a new axes is ...
    created unless parent is
%                 given, ex, parent may be a ...
    subplot
%       -iflip, flip the intensities as ...
    they go outward radially, ie,
%                 highest values are placed ...
    nearest the origin [{0} 1]
%       -inorm, normalize intensities, ...
    means all angles will have 100%
%       -incout, if 0, data outside di ...
    limits will not be used [0 {1}]
%
%   Output:
%      HANDLES   Handles of all lines, ...
    fills, texts
%      DATA   Wind rose occurences per ...
    direction and intensity
%
%   Examle:
%      d=0:10:350;
%      D=[];
%      V=[];
%      for i=1:length(d)
%        n=d(i)/10;
%        D=[D ones(1,n)*d(i)];
```

```
%       V=[V 1:n];
%     end
%
%     figure
%     wind_rose(D,V)
%
%     figure
%     wind_rose(D,V,'iflip',1)
%
%     figure
%     wind_rose(D,V,'ci',[1 2 ...
    7],'dtype','meteo')
%
%     % place it on a previous axes:
%     ax=axes;
%     plot(lon,lat)
%     wind_rose(D,V,'ax',[ax x y 1/3])
%
%   MMA 26-11-2007, mma@odyle.net
%
%   IEO, Instituto Espanol de Oceanografia
%   La Coruna, Espana

%   10-12-2007 - Added varargin ci and n ...
    (nAngles removed as input)
%   17-12-2007 - Added varargin ax, colors
%   22-02-2008 - Added varargin dtype
%   08-05-2008 - Bug fix (bar at dir=0 ...
    could be incorrect in some cases)
%   14-05-2008 - Added varargin iflip
%   16-06-2008 - Added varargin parent
%   10-06-2009 - Added varargin incout
%   27-04-2010 - Added output DATA
%   17-06-2010 - Bug fix ...
    (E(i,end)=length(find(b≥Ag(end-1))),
%                 previously was ...
    ...b>Ag...). So the percentages where
%                 wrong only when using ...
    intensities equal to the lower
%                 value of the highest ...
    intensity subdivision, basically
%                 an academic case.

handles=[];

% varargin options:
dtype='standard';
nAngles=36;
ri=1/30;
quad=1;
legType=2;
percBg='w';
titStr='';
legStr='';
cmap=jet;
colors=[];
Ag=[]; % intensity subdivs.
ci=[]; % percentage circles
lineColors='k';
borderColor='none';
onAxes=false;
iflip=0;
inorm=0;
parent=0;
IncHiLow=1; % include values higher and ...
    lower that the limits of Ag.

vin=varargin;
for i=1:length(vin)
  if isequal(vin{i},'dtype')
    dtype=vin{i+1};
  elseif isequal(vin{i},'n')
    nAngles=vin{i+1};
  elseif isequal(vin{i},'ri')
    ri=vin{i+1};
  elseif isequal(vin{i},'quad')
    quad=vin{i+1};
  elseif isequal(vin{i},'legtype')
    legType=vin{i+1};
  elseif isequal(vin{i},'percbg')
```

```
    percBg=vin{i+1};
  elseif isequal(vin{i},'labtitle')
    titStr=vin{i+1};
  elseif isequal(vin{i},'lablegend')
    legStr=vin{i+1};
  elseif isequal(vin{i},'cmap')
    cmap=vin{i+1};
  elseif isequal(vin{i},'colors')
    colors=vin{i+1};
  elseif isequal(vin{i},'di')
    Ag=vin{i+1};
  elseif isequal(vin{i},'ci')
    ci=vin{i+1};
  elseif isequal(vin{i},'lcolor')
    lineColors=vin{i+1};
  elseif isequal(vin{i},'bcolor')
    borderColor=vin{i+1};
  elseif isequal(vin{i},'ax')
    ax=vin{i+1};
    try
      onAxes=ax(1);
      onAxesX=ax(2);
      onAxesY=ax(3);
      onAxesR=ax(4);
    catch
      disp(':: cannot place wind rose on ...
          axes, bad argument for ax')
      return
    end
  elseif isequal(vin{i},'iflip')
    iflip=vin{i+1};
  elseif isequal(vin{i},'inorm')
    inorm=vin{i+1};
  elseif isequal(vin{i},'parent')
    parent=vin{i+1};
  elseif isequal(vin{i},'incout')
    IncHiLow=vin{i+1};
  end
end

% other options:
% size of the full rectangle:
rs=1.2;
rl=1.7;

% directions conversion:
if isequal(dtype,'meteo')
  D=mod(-90-D,360);
end


% angles subdivisons:
D=mod(D,360);
Ay=linspace(0,360,nAngles+1)- 0.5*360/nAngles;

% calc instensity subdivisions:
if isempty(Ag)
  % gen Ag:
  f=figure('visible','off');
  plot(F); axis tight;
  yl=get(gca,'ytick');
  close(f)
  dyl=diff(yl); dyl=dyl(1);
  if min(F)<yl(1),   yl=[yl(1)-dyl yl];   end
  if max(F)>yl(end), yl=[yl yl(end)+dyl]; end
  Ag=yl;
end

for i=1:length(Ay)-1
  if i==1
     I=find( (D≥Ay(i) & D<Ay(i+1)) | ...
         D≥Ay(end));
  else
    I=find(D≥Ay(i) & D<Ay(i+1));
  end
  b=F(I);

  for j=1:length(Ag)-1
    if j==length(Ag)-1
      J=find(b≥Ag(j) & b≤Ag(j+1)); % ...
```

```
          include data with last Agg
    else
      J=find(b≥Ag(j) & b<Ag(j+1));
    end
    E(i,j)=length(J);
  end

  if IncHiLow
    E(i,1)=length(find(b<Ag(2)));
    E(i,end)=length(find(b≥Ag(end−1)));
  end
end
b=sum(E,2)/length(D)*100;

% normalize data:
if inorm
  n=sum(E,2);
  for i=1:length(n)
    E(i,:)=E(i,:)/n(i);
  end
  b=100*ones(size(b));
end

% check if has values higher or lower than ...
    the Ag limits
hasH=length(find(F>Ag(end)));
hasL=length(find(F<Ag(1)));

% calc number of percentage circles to draw:
if isempty(ci)
  if inorm
    ci=[25 50 75];
    g=120;
    ncircles=3;
  else
    dcircles=[1 2 5 10 15 20 25 30 50];
    ncircles=3;
    d=abs(1./(dcircles/max(b))−ncircles);
    i=find(d==min(d));
    d=dcircles(i(1));
    if d*ncircles<max(b)
      ncircles=ncircles+1;
    end
    ci=[1:ncircles]*d;
    g=ncircles*d;
  end
else
  ncircles=length(ci);
  g=max(max(ci),max(b));
end

% plot axes, percentage circles and ...
    percent. data:
if parent
  wrAx=parent;
  set(wrAx,'units','normalized');
else
  wrAx=axes('units','normalized');
end
ri=g*ri;
handles(end+1)=fill([−rs*g rl*g rl*g ...
    −rs*g],[−rs*g −rs*g rs*g rs*g],'w',...
                     'EdgeColor',borderColor);
if onAxes
  set(handles(end),'facecolor','none')
end
hold on
handles(end+1)=plot([−g−ri −ri nan ri g+ri ...
    nan 0 0 nan 0 0],...
                    [0 0 nan 0 0 nan −g−ri ...
                        −ri nan ri ...
                    g+ri],':','color',...
                    lineColors);
t0=[0:360]*pi/180;
labs=[];
Ang=[1/4 3/4 5/4 7/4]*pi;
Valign={'top' 'top' 'bottom' 'bottom'};
Halign={'right' 'left' 'left' 'right'};
for i=1:ncircles
  x=(ci(i)+ri)*cos(t0);
```

```
  y=(ci(i)+ri)*sin(t0);

  circles(i)=plot(x,y,':','color',lineColors);
  handles(end+1)=circles(i);

  labs(i)=text((ci(i)+ri)*cos(Ang(quad)), ...
      (ci(i)+ri)*sin(Ang(quad)),[num2str(ci(i)),...
  '%'],...
      'VerticalAlignment', ...
          Valign{quad},'HorizontalAlignment', ...
          Halign{quad},...
      'BackgroundColor',percBg,'FontSize',8);
end
handles=[handles labs];

% calc colors:
if isempty(colors)
  cor={};
  for j=1:length(Ag)-1
    cor{j}=caxcolor(Ag(j),[Ag(1) ...
        Ag(end-1)],cmap);
  end
else
  cor=colors;
end

% fill data:
n=sum(E,2);
if iflip, E=fliplr(E); end
for i=1:length(Ay)-1
  if n(i)
    t=linspace(Ay(i),Ay(i+1),20)*pi/180;
    r1=ri;
    for j=1:length(Ag)-1
      r2=E(i,j)/n(i) *b(i) +r1;

      x=[r1*cos(t(1)) r2*cos(t) ...
          r1*cos(fliplr(t))];
      y=[r1*sin(t(1)) r2*sin(t) ...
          r1*sin(fliplr(t))];

      if iflip, jcor=length(Ag)-1-j+1;
      else, jcor=j;
      end

      if E(i,j)>0, ...
          handles(end+1)=fill(x,y,cor{jcor}); ...
          end
      r1=r2;
    end
  end
end
axis equal
axis off

% uistack has problems in some matlab ...
    versions, so:
%uistack(labs,'top')
%uistack(circles,'top')
ch=get(wrAx,'children');
if inorm
  % only bring circles up in inorm case.
  for i=1:length(circles)
    ch(ch==circles(i))=[]; ch=[circles(i); ch];
  end
end
for i=1:length(labs)
  ch(ch==labs(i))=[]; ch=[labs(i); ch];
end
set(wrAx,'children',ch);


% N S E W labels:
bg='none';
args={'BackgroundColor',bg,'FontSize',8};
h(1)=text(-g-ri, 0,'WEST', ...
    'VerticalAlignment','top',   ...
    'HorizontalAlignment','left', args{:});
h(2)=text( g+ri, 0,'EAST', ...
    'VerticalAlignment','top',   ...
```

```
    'HorizontalAlignment','right',args{:});
h(3)=text( ...
    0,-g-ri,'SOUTH','VerticalAlignment',...
'bottom','HorizontalAlignment','left', ...
    args{:});
h(4)=text( 0, ...
    g+ri,'NORTH','VerticalAlignment','top', ...
      'HorizontalAlignment','left', args{:});
handles=[handles h];

% scale legend:
L=(g*rl-g-ri)/7;
h=(g+ri)/10;
dy=h/3;

x0=g+ri+(g*rl-g-ri)/7;
x1=x0+L;
y0=-g-ri;

if legType==1 % contimuous.
  for j=1:length(Ag)-1
    lab=num2str(Ag(j));
    if j==1 & hasL & IncHiLow
      lab='';
    end
    y1=y0+h;
    handles(end+1)=fill([x0 x1 x1 x0],[y0 ...
        y0 y1 y1],cor{j});
    handles(end+1)=text(x1+L/4,y0,lab,...
    'VerticalAlignment','middle','fontsize',8);
    y0=y1;
  end
  if ¬ (hasH & IncHiLow)
    handles(end+1)=text(x1+L/4,y0,...
    num2str(Ag(end)),'VerticalAlignment',...
    'middle','fontsize',8);
  end
elseif legType==2 % separated boxes.
  for j=1:length(Ag)-1
    lab=[num2str(Ag(j)) ' - ' ...
        num2str(Ag(j+1))];
    if j==1 & hasL & IncHiLow
      lab=['<',num2str(Ag(2))];
    end
    if j==length(Ag)-1 & hasH & IncHiLow
      lab=['≥',num2str(Ag(j))];
    end
    y1=y0+h;
    handles(end+1)=fill([x0 x1 x1 ...
        x0],[y0+dy y0+dy y1 y1],cor{j});
    handles(end+1)=text(x1+L/4,(y0+dy+y1)/2,...
    lab,'VerticalAlignment',...
    'middle','fontsize',8);
    y0=y1;
  end

end

% title and legend label:
x=mean([-g*rs,g*rl]);
y=mean([g+ri,g*rs]);
handles(end+1)=text(x,y,titStr,...
'HorizontalAlignment','center');

x=x0;
y=y1+dy;
handles(end+1)=text(x,y,legStr,...
'HorizontalAlignment','left',...
'VerticalAlignment','bottom');

if onAxes
  place_wr(onAxes,wrAx,onAxesX,onAxesY,onAxesR);
end

if nargout≥1
  varargout{1}=handles;
end
if nargout≥2
  varargout{2}=E;
end
```

```
function place_wr(ax,ax2,x,y,width)
if nargin < 5
  width=1/5;
end
uax=get(ax,'units');
pax=get(ax,'position');
set(ax,'units',uax)
axXlim=get(ax,'xlim');
axYlim=get(ax,'ylim');

x_ax2=pax(1)+pax(3)*(x-axXlim(1))/diff(axXlim);
y_ax2=pax(2)+pax(4)*(y-axYlim(1))/diff(axYlim);

pax2=get(ax2,'position');
width=pax(3)*width;
height=pax2(4)*width/pax2(3);
pax2=[x_ax2 y_ax2 width height];

if 1
  % place at centre of the wr, not the ...
      bottom left corner:
  ax2Xlim=get(ax2,'xlim');
  ax2Ylim=get(ax2,'ylim');
  dx=(0-ax2Xlim(1))/diff(ax2Xlim)*pax2(3);
  dy=(0-ax2Ylim(1))/diff(ax2Ylim)*pax2(4);
  x_ax2=x_ax2-dx;
  y_ax2=y_ax2-dy;
  pax2=[x_ax2 y_ax2 width height];
end
set(ax2,'position',pax2)



function cor = caxcolor(val,cax,cmap)
%CAXCOLOR   Caxis color for value
%   Find the color for a given value in a ...
    colormap.
%
%   Syntax:
%      COLOR = CAXCOLOR(VALUE,CAXIS,COLORMAP)
%
%   Inputs:
%      VALUE
%      CAXIS   Default is current caxis
%      COLORMAP   Default is current colormap
%
%   Output:
%      COLOR   RGB color vector
%
%   Example:
%      figure
%      pcolor(peaks)
%      color=caxcolor(0);
%      set(gcf,'color',color)
%
%   MMA 28-5-2007, martinho@fis.ua.pt

% Department of Physics
% University of Aveiro, Portugal

if nargin < 3
  cmap = get(gcf,'colormap');
end
if nargin < 2
  cax = caxis;
end

n=size(cmap,1);
i= (val-cax(1))/diff(cax) * (n-1) +1;
a=i-floor(i);
i=floor(i);

i=min(i,n);
i=max(i,1);

if i==n
  cor=cmap(n,:);
elseif i==1
  cor=cmap(1,:);
```

```
else
  cor=cmap(i,:)*(1-a) + cmap(i+1,:)*a;
end
```

.3 Tide table of 2019

		HIGH TIDE				LOW TIDE						
DATE		AM		PM		AM		PM		Rng.	Rng.	Avg.
		Hr.	Ht.	Hr.	Ht.	Hr.	Ht.	Hr.	Ht.	AM	PM	
01/01/19				13:18	4.01	6:46	1.78	19:25	1.68		2.33	2.33
02/01/19		1:48	4.04	14:15	4.07	7:48	1.68	20:17	1.59	2.36	2.48	2.42
03/01/19		2:37	4.17	15:03	4.14	8:40	1.56	21:03	1.50	2.61	2.64	2.63
04/01/19		3:21	4.30	15:45	4.21	9:26	1.43	21:44	1.41	2.87	2.80	2.84
05/01/19		4:00	4.41	16:22	4.25	10:07	1.34	22:22	1.35	3.07	2.90	2.99
06/01/19	N	4:36	4.48	16:57	4.27	10:45	1.27	22:58	1.33	3.21	2.94	3.08
07/01/19		5:10	4.50	17:30	4.25	11:22	1.26	23:32	1.35	3.24	2.90	3.07
08/01/19		5:44	4.48	18:03	4.20	11:56	1.29			3.19		3.19
09/01/19		6:17	4.42	18:35	4.12	0:06	1.41	12:31	1.35	3.01	2.77	2.89
10/01/19		6:52	4.33	19:10	4.02	0:40	1.50	13:05	1.45	2.83	2.57	2.70
11/01/19		7:28	4.21	19:47	3.90	1:15	1.61	13:42	1.57	2.60	2.33	2.47
12/01/19		8:09	4.07	20:30	3.78	1:54	1.74	14:22	1.70	2.33	2.08	2.21
13/01/19		8:55	3.93	21:22	3.68	2:37	1.87	15:09	1.83	2.06	1.85	1.96
14/01/19	C	9:51	3.81	22:26	3.62	3:30	1.98	16:05	1.92	1.83	1.70	1.77
15/01/19		10:57	3.75	23:38	3.66	4:34	2.05	17:11	1.94	1.70	1.72	1.71
16/01/19				12:08	3.78	5:46	2.01	18:19	1.87		1.91	1.91
17/01/19		0:46	3.80	13:16	3.92	6:56	1.86	19:23	1.70	1.94	2.22	2.08
18/01/19		1:47	4.03	14:15	4.14	7:57	1.62	20:19	1.46	2.41	2.68	2.55
19/01/19		2:40	4.30	15:08	4.38	8:51	1.32	21:10	1.22	2.98	3.16	3.07
20/01/19		3:30	4.58	15:58	4.60	9:42	1.03	21:58	1.00	3.55	3.60	3.58
21/01/19	LL	4:17	4.82	16:46	4.75	10:31	0.78	22:46	0.83	4.04	3.92	3.98
22/01/19		5:05	4.99	17:34	4.82	11:19	0.62	23:33	0.76	4.37	4.06	4.22
23/01/19		5:52	5.05	18:22	4.78			12:06	0.59		4.19	4.19
24/01/19		6:41	5.00	19:10	4.64	0:20	0.79	12:54	0.69	4.21	3.95	4.08
25/01/19		7:30	4.83	19:59	4.43	1:08	0.91	13:43	0.90	3.92	3.53	3.73
26/01/19		8:21	4.58	20:52	4.19	1:57	1.12	14:35	1.18	3.46	3.01	3.24
27/01/19	M	9:17	4.28	21:51	3.95	2:50	1.38	15:30	1.47	2.90	2.48	2.69
28/01/19		10:19	3.99	22:58	3.79	3:49	1.64	16:32	1.73	2.35	2.06	2.21
29/01/19		11:32	3.78			4:57	1.84	17:42	1.89	1.94		1.94
30/01/19		0:12	3.73	12:50	3.71	6:14	1.92	18:55	1.91	1.81	1.80	1.81
31/01/19		1:21	3.80	13:58	3.76	7:27	1.87	19:57	1.82	1.93	1.94	1.94
01/02/19		2:20	3.94	14:51	3.87	8:27	1.73	20:48	1.68	2.21	2.19	2.20
02/02/19		3:07	4.10	15:34	4.00	9:15	1.56	21:30	1.53	2.54	2.47	2.51
03/02/19		3:46	4.26	16:10	4.12	9:55	1.40	22:08	1.40	2.86	2.72	2.79

04/02/19	N	4:21	4.38	16:42	4.20	10:31	1.28	22:42	1.30	3.10	2.90	3.00
05/02/19		4:54	4.46	17:13	4.26	11:04	1.20	23:15	1.25	3.26	3.01	3.14
06/02/19		5:25	4.50	17:42	4.27	11:36	1.17	23:46	1.25	3.33	3.02	3.18
07/02/19		5:56	4.50	18:12	4.25			12:07	1.18		3.07	3.07
08/02/19		6:28	4.45	18:43	4.19	0:17	1.28	12:38	1.24	3.17	2.95	3.06
09/02/19		7:01	4.36	19:16	4.10	0:49	1.35	13:10	1.34	3.01	2.76	2.89
10/02/19		7:36	4.23	19:52	3.98	1:23	1.46	13:46	1.46	2.77	2.52	2.65
11/02/19		8:16	4.08	20:35	3.85	2:01	1.60	14:26	1.61	2.48	2.24	2.36
12/02/19	C	9:03	3.90	21:29	3.72	2:45	1.75	15:14	1.77	2.15	1.95	2.05
13/02/19		10:03	3.75	22:39	3.65	3:42	1.89	16:15	1.90	1.86	1.75	1.81
14/02/19		11:21	3.68			4:54	1.97	17:31	1.93	1.71		1.71
15/02/19		0:02	3.70	12:46	3.77	6:18	1.89	18:51	1.81	1.81	1.96	1.89
16/02/19		1:19	3.90	13:57	4.00	7:34	1.65	19:59	1.56	2.25	2.44	2.35
17/02/19		2:22	4.21	14:55	4.29	8:36	1.31	20:55	1.25	2.90	3.04	2.97
18/02/19		3:16	4.54	15:47	4.57	9:29	0.96	21:45	0.95	3.58	3.62	3.60
19/02/19	LL	4:05	4.85	16:34	4.78	10:18	0.66	22:32	0.72	4.19	4.06	4.13
20/02/19		4:52	5.06	17:19	4.89	11:04	0.48	23:18	0.60	4.58	4.29	4.44
21/02/19		5:38	5.15	18:03	4.88	11:49	0.44			4.71		4.71
22/02/19		6:23	5.09	18:47	4.76	0:02	0.60	12:34	0.56	4.49	4.20	4.35
23/02/19		7:07	4.89	19:31	4.54	0:47	0.72	13:18	0.80	4.17	3.74	3.96
24/02/19		7:53	4.59	20:17	4.27	1:32	0.96	14:03	1.13	3.63	3.14	3.39
25/02/19		8:41	4.23	21:08	3.98	2:20	1.27	14:51	1.48	2.96	2.50	2.73
26/02/19	M	9:37	3.88	22:10	3.74	3:13	1.60	15:47	1.81	2.28	1.93	2.11
27/02/19		10:49	3.60	23:27	3.61	4:17	1.88	16:57	2.04	1.72	1.57	1.65
28/02/19				12:17	3.49	5:38	2.03	18:21	2.10		1.39	1.39
01/03/19		0:50	3.63	13:37	3.56	7:02	2.00	19:35	2.00	1.63	1.56	1.60
02/03/19		1:57	3.78	14:34	3.72	8:09	1.84	20:30	1.81	1.94	1.91	1.93
03/03/19		2:47	3.97	15:16	3.90	8:57	1.64	21:12	1.61	2.33	2.29	2.31
04/03/19		3:26	4.16	15:50	4.06	9:36	1.44	21:49	1.43	2.72	2.63	2.68
05/03/19		4:00	4.32	16:21	4.21	10:10	1.28	22:22	1.29	3.04	2.92	2.98
06/03/19	N	4:32	4.45	16:50	4.31	10:41	1.16	22:52	1.18	3.29	3.13	3.21
07/03/19		5:02	4.54	17:18	4.37	11:11	1.09	23:22	1.13	3.45	3.24	3.35
08/03/19		5:32	4.57	17:46	4.40	11:40	1.07	23:52	1.13	3.50	3.27	3.39
09/03/19		6:03	4.55	18:16	4.37			12:09	1.10		3.27	3.27
10/03/19		6:34	4.48	18:47	4.30	0:23	1.17	12:40	1.18	3.31	3.12	3.22
11/03/19		7:08	4.35	19:22	4.18	0:56	1.27	13:14	1.31	3.08	2.87	2.98
12/03/19		7:46	4.18	20:02	4.03	1:33	1.41	13:53	1.48	2.77	2.55	2.66
13/03/19		8:31	3.97	20:52	3.85	2:16	1.59	14:39	1.69	2.38	2.16	2.27

14/03/19	C	9:30	3.77	22:01	3.71	3:10	1.77	15:39	1.88	2.00	1.83	1.92
15/03/19		10:53	3.64	23:31	3.70	4:23	1.90	16:58	1.97	1.74	1.73	1.74
16/03/19				12:27	3.71	5:53	1.87	18:28	1.88		1.83	1.83
17/03/19		0:58	3.89	13:43	3.96	7:17	1.62	19:42	1.61	2.27	2.35	2.31
18/03/19		2:06	4.21	14:42	4.28	8:21	1.27	20:40	1.26	2.94	3.02	2.98
19/03/19		3:01	4.56	15:31	4.58	9:14	0.91	21:29	0.94	3.65	3.64	3.65
20/03/19		3:49	4.87	16:16	4.81	10:01	0.63	22:15	0.69	4.24	4.12	4.18
21/03/19	LL	4:35	5.07	16:59	4.92	10:45	0.47	22:59	0.56	4.60	4.36	4.48
22/03/19		5:18	5.13	17:40	4.92	11:27	0.47	23:41	0.56	4.66	4.36	4.51
23/03/19		6:00	5.04	18:21	4.80			12:08	0.61		4.19	4.19
24/03/19		6:42	4.82	19:01	4.59	0:24	0.70	12:49	0.86	4.12	3.73	3.93
25/03/19		7:24	4.51	19:43	4.32	1:06	0.95	13:31	1.19	3.56	3.13	3.35
26/03/19		8:08	4.15	20:29	4.04	1:51	1.27	14:15	1.54	2.88	2.50	2.69
27/03/19		8:59	3.80	21:26	3.77	2:41	1.60	15:06	1.87	2.20	1.90	2.05
28/03/19	M	10:05	3.52	22:41	3.59	3:41	1.90	16:13	2.12	1.62	1.47	1.55
29/03/19		11:36	3.39			4:59	2.08	17:40	2.21	1.31		1.31
30/03/19		0:07	3.57	13:04	3.46	6:27	2.07	19:02	2.12	1.50	1.34	1.42
31/03/19		1:21	3.69	14:04	3.64	7:38	1.92	20:01	1.92	1.77	1.72	1.75
01/04/19		2:15	3.88	14:47	3.84	8:28	1.71	20:45	1.70	2.17	2.14	2.16
02/04/19		2:56	4.08	15:21	4.04	9:07	1.50	21:21	1.49	2.58	2.55	2.57
03/04/19		3:31	4.27	15:52	4.21	9:40	1.32	21:54	1.32	2.95	2.89	2.92
04/04/19		4:03	4.42	16:21	4.36	10:11	1.18	22:25	1.19	3.24	3.17	3.21
05/04/19	N	4:34	4.53	16:50	4.46	10:41	1.08	22:55	1.10	3.45	3.36	3.41
06/04/19		5:05	4.60	17:19	4.51	11:10	1.03	23:26	1.06	3.57	3.45	3.51
07/04/19		5:37	4.60	17:50	4.51	11:41	1.04	23:58	1.08	3.56	3.43	3.50
08/04/19		6:10	4.54	18:23	4.45			12:13	1.11		3.34	3.34
09/04/19		6:45	4.41	18:59	4.34	0:33	1.16	12:49	1.25	3.25	3.09	3.17
10/04/19		7:26	4.23	19:41	4.17	1:12	1.31	13:29	1.44	2.92	2.73	2.83
11/04/19		8:14	4.01	20:34	3.98	1:58	1.49	14:18	1.65	2.52	2.33	2.43
12/04/19	C	9:17	3.79	21:45	3.82	2:55	1.68	15:20	1.86	2.11	1.96	2.04
13/04/19		10:42	3.67	23:15	3.80	4:10	1.81	16:41	1.96	1.86	1.84	1.85
14/04/19				12:13	3.75	5:39	1.78	18:10	1.87		1.88	1.88
15/04/19		0:40	3.97	13:27	3.99	7:00	1.55	19:23	1.60	2.42	2.39	2.41
16/04/19		1:48	4.25	14:23	4.29	8:02	1.24	20:20	1.28	3.01	3.01	3.01
17/04/19		2:42	4.55	15:11	4.56	8:54	0.94	21:09	0.98	3.61	3.58	3.60
18/04/19		3:30	4.80	15:55	4.75	9:39	0.73	21:54	0.77	4.07	3.98	4.03
19/04/19	LL	4:14	4.94	16:36	4.85	10:22	0.63	22:37	0.67	4.31	4.18	4.25
20/04/19		4:56	4.96	17:16	4.85	11:03	0.66	23:19	0.69	4.30	4.16	4.23

21/04/19		5:37	4.85	17:54	4.75	11:42	0.80			4.05		4.05
22/04/19		6:17	4.64	18:33	4.57	0:01	0.82	12:22	1.02	3.82	3.55	3.69
23/04/19		6:57	4.37	19:14	4.34	0:43	1.04	13:02	1.30	3.33	3.04	3.19
24/04/19		7:39	4.07	19:58	4.09	1:26	1.32	13:44	1.60	2.75	2.49	2.62
25/04/19		8:27	3.78	20:50	3.85	2:13	1.61	14:33	1.88	2.17	1.97	2.07
26/04/19		9:27	3.54	21:57	3.66	3:09	1.87	15:34	2.11	1.67	1.55	1.61
27/04/19	M	10:47	3.41	23:15	3.59	4:19	2.04	16:53	2.22	1.37	1.37	1.37
28/04/19				12:12	3.43	5:39	2.08	18:15	2.17		1.26	1.26
29/04/19		0:30	3.65	13:17	3.58	6:51	1.97	19:18	2.01	1.68	1.57	1.63
30/04/19		1:29	3.80	14:04	3.78	7:45	1.79	20:06	1.80	2.01	1.98	2.00
01/05/19		2:16	3.99	14:43	3.98	8:28	1.60	20:46	1.60	2.39	2.38	2.39
02/05/19		2:55	4.18	15:16	4.18	9:04	1.41	21:21	1.41	2.77	2.77	2.77
03/05/19		3:30	4.34	15:48	4.35	9:37	1.25	21:54	1.25	3.09	3.10	3.10
04/05/19		4:03	4.48	16:20	4.48	10:08	1.13	22:27	1.13	3.35	3.35	3.35
05/05/19	N	4:37	4.56	16:52	4.57	10:41	1.06	23:01	1.06	3.50	3.51	3.51
06/05/19		5:12	4.59	17:27	4.60	11:15	1.04	23:37	1.04	3.55	3.56	3.56
07/05/19		5:49	4.54	18:03	4.56	11:51	1.10			3.44		3.44
08/05/19		6:30	4.43	18:45	4.45	0:17	1.10	12:31	1.22	3.33	3.23	3.28
09/05/19		7:15	4.26	19:32	4.29	1:00	1.22	13:16	1.40	3.04	2.89	2.97
10/05/19		8:09	4.05	20:29	4.12	1:51	1.38	14:09	1.60	2.67	2.52	2.60
11/05/19		9:15	3.86	21:40	3.98	2:51	1.55	15:13	1.77	2.31	2.21	2.26
12/05/19	C	10:34	3.78	23:02	3.96	4:04	1.65	16:30	1.85	2.13	2.11	2.12
13/05/19		11:55	3.84			5:24	1.63	17:50	1.78	2.21		2.21
14/05/19		0:20	4.07	13:04	4.02	6:38	1.49	19:00	1.58	2.58	2.44	2.51
15/05/19		1:26	4.25	14:00	4.24	7:39	1.28	19:57	1.34	2.97	2.90	2.94
16/05/19		2:21	4.45	14:49	4.45	8:30	1.09	20:47	1.12	3.36	3.33	3.35
17/05/19		3:09	4.60	15:32	4.60	9:16	0.96	21:33	0.96	3.64	3.64	3.64
18/05/19	LL	3:54	4.68	16:13	4.69	9:59	0.90	22:17	0.89	3.78	3.80	3.79
19/05/19		4:36	4.67	16:53	4.69	10:39	0.93	22:59	0.90	3.74	3.79	3.77
20/05/19		5:16	4.58	17:32	4.63	11:19	1.03	23:41	1.00	3.55	3.63	3.59
21/05/19		5:55	4.43	18:10	4.51	11:58	1.18			3.25		3.25
22/05/19		6:35	4.23	18:50	4.34	0:22	1.16	12:37	1.38	3.07	2.96	3.02
23/05/19		7:15	4.02	19:32	4.15	1:05	1.36	13:19	1.60	2.66	2.55	2.61
24/05/19		7:59	3.81	20:20	3.95	1:49	1.57	14:05	1.82	2.24	2.13	2.19
25/05/19		8:51	3.62	21:15	3.78	2:39	1.77	14:58	2.00	1.85	1.78	1.82
26/05/19	M	9:54	3.50	22:20	3.67	3:37	1.93	16:02	2.13	1.57	1.54	1.56
27/05/19		11:08	3.46	23:30	3.66	4:43	2.00	17:15	2.15	1.46	1.51	1.49
28/05/19				12:16	3.54	5:52	1.98	18:22	2.06		1.48	1.48

29/05/19		0:34	3.74	13:12	3.70	6:51	1.87	19:17	1.91	1.87	1.79	1.83
30/05/19		1:27	3.88	13:57	3.89	7:40	1.71	20:03	1.72	2.17	2.17	2.17
31/05/19		2:13	4.04	14:37	4.09	8:22	1.54	20:43	1.53	2.50	2.56	2.53
01/06/19		2:54	4.21	15:14	4.28	9:00	1.37	21:22	1.34	2.84	2.94	2.89
02/06/19		3:33	4.36	15:51	4.45	9:37	1.22	22:00	1.18	3.14	3.27	3.21
03/06/19	N	4:12	4.48	16:29	4.57	10:14	1.11	22:39	1.06	3.37	3.51	3.44
04/06/19		4:52	4.54	17:08	4.64	10:53	1.06	23:21	1.00	3.48	3.64	3.56
05/06/19		5:35	4.54	17:50	4.64	11:34	1.07			3.47		3.47
06/06/19		6:20	4.46	18:37	4.58	0:05	1.00	12:19	1.15	3.46	3.43	3.45
07/06/19		7:10	4.33	19:28	4.46	0:53	1.07	13:08	1.28	3.26	3.18	3.22
08/06/19		8:05	4.17	20:26	4.32	1:46	1.19	14:03	1.44	2.98	2.88	2.93
09/06/19		9:08	4.01	21:32	4.19	2:46	1.34	15:04	1.58	2.67	2.61	2.64
10/06/19	C	10:18	3.92	22:43	4.11	3:51	1.46	16:12	1.67	2.46	2.44	2.45
11/06/19		11:30	3.91	23:55	4.10	5:02	1.52	17:24	1.68	2.39	2.42	2.41
12/06/19				12:36	3.99	6:10	1.50	18:32	1.59		2.40	2.40
13/06/19		1:01	4.16	13:35	4.12	7:12	1.42	19:33	1.46	2.74	2.66	2.70
14/06/19		2:00	4.24	14:26	4.27	8:07	1.33	20:27	1.32	2.91	2.95	2.93
15/06/19		2:51	4.32	15:12	4.39	8:55	1.24	21:15	1.21	3.08	3.18	3.13
16/06/19		3:37	4.37	15:55	4.48	9:38	1.19	22:01	1.13	3.18	3.35	3.27
17/06/19	LL	4:20	4.37	16:35	4.52	10:20	1.18	22:44	1.11	3.19	3.41	3.30
18/06/19		5:00	4.34	17:14	4.51	11:00	1.21	23:25	1.14	3.13	3.37	3.25
19/06/19		5:38	4.26	17:52	4.46	11:38	1.29			2.97		2.97
20/06/19		6:15	4.16	18:30	4.35	0:05	1.22	12:17	1.40	2.94	2.95	2.95
21/06/19		6:53	4.03	19:09	4.22	0:44	1.34	12:56	1.53	2.69	2.69	2.69
22/06/19		7:32	3.89	19:50	4.07	1:25	1.48	13:37	1.68	2.41	2.39	2.40
23/06/19		8:15	3.75	20:36	3.93	2:07	1.63	14:21	1.83	2.12	2.10	2.11
24/06/19		9:04	3.63	21:28	3.80	2:53	1.77	15:12	1.96	1.86	1.84	1.85
25/06/19	M	10:02	3.56	22:27	3.72	3:46	1.89	16:11	2.05	1.67	1.67	1.67
26/06/19		11:07	3.55	23:31	3.70	4:46	1.94	17:16	2.06	1.61	1.64	1.63
27/06/19				12:11	3.63	5:48	1.92	18:19	1.99		1.64	1.64
28/06/19		0:33	3.77	13:07	3.78	6:46	1.83	19:16	1.84	1.94	1.94	1.94
29/06/19		1:29	3.90	13:57	3.97	7:37	1.68	20:06	1.65	2.22	2.32	2.27
30/06/19		2:19	4.06	14:42	4.18	8:24	1.50	20:52	1.44	2.56	2.74	2.65
01/07/19		3:06	4.24	15:26	4.39	9:08	1.32	21:37	1.22	2.92	3.17	3.05
02/07/19	N	3:51	4.40	16:09	4.57	9:52	1.16	22:22	1.03	3.24	3.54	3.39
03/07/19		4:37	4.52	16:54	4.71	10:36	1.04	23:08	0.89	3.48	3.82	3.65
04/07/19		5:23	4.59	17:40	4.78	11:22	0.99	23:55	0.82	3.60	3.96	3.78
05/07/19		6:11	4.57	18:29	4.77			12:09	1.00		3.77	3.77

06/07/19		7:01	4.49	19:20	4.69	0:45	0.85	12:58	1.07	3.64	3.62	3.63
07/07/19		7:54	4.35	20:14	4.54	1:36	0.96	13:51	1.20	3.39	3.34	3.37
08/07/19		8:50	4.19	21:13	4.36	2:31	1.13	14:47	1.37	3.06	2.99	3.03
09/07/19	C	9:52	4.03	22:17	4.17	3:29	1.32	15:48	1.53	2.71	2.64	2.68
10/07/19		10:58	3.93	23:26	4.03	4:32	1.50	16:55	1.65	2.43	2.38	2.41
11/07/19				12:06	3.91	5:39	1.61	18:04	1.69		2.22	2.22
12/07/19		0:37	3.97	13:10	3.96	6:45	1.64	19:12	1.65	2.33	2.31	2.32
13/07/19		1:42	3.98	14:08	4.07	7:45	1.60	20:11	1.55	2.38	2.52	2.45
14/07/19		2:38	4.04	14:57	4.20	8:38	1.52	21:03	1.43	2.52	2.77	2.65
15/07/19		3:26	4.11	15:41	4.32	9:23	1.43	21:49	1.32	2.68	3.00	2.84
16/07/19	LL	4:08	4.17	16:21	4.41	10:05	1.36	22:31	1.24	2.81	3.17	2.99
17/07/19		4:46	4.20	16:58	4.46	10:44	1.31	23:09	1.21	2.89	3.25	3.07
18/07/19		5:21	4.21	17:34	4.46	11:21	1.31	23:46	1.22	2.90	3.24	3.07
19/07/19		5:54	4.18	18:08	4.41	11:57	1.35			2.83		2.83
20/07/19		6:28	4.12	18:43	4.33	0:21	1.27	12:32	1.42	2.85	2.91	2.88
21/07/19		7:02	4.03	19:19	4.22	0:56	1.37	13:07	1.53	2.66	2.69	2.68
22/07/19		7:37	3.93	19:57	4.09	1:32	1.49	13:44	1.65	2.44	2.44	2.44
23/07/19		8:17	3.81	20:40	3.95	2:10	1.62	14:25	1.79	2.19	2.16	2.18
24/07/19		9:04	3.70	21:30	3.81	2:53	1.76	15:12	1.92	1.94	1.89	1.92
25/07/19	M	10:01	3.63	22:30	3.71	3:43	1.88	16:10	2.02	1.75	1.69	1.72
26/07/19		11:07	3.61	23:39	3.69	4:42	1.95	17:18	2.04	1.66	1.65	1.66
27/07/19				12:17	3.70	5:49	1.94	18:28	1.95		1.75	1.75
28/07/19		0:48	3.77	13:20	3.87	6:55	1.83	19:32	1.76	1.94	2.11	2.03
29/07/19		1:51	3.94	14:16	4.11	7:54	1.64	20:28	1.50	2.30	2.61	2.46
30/07/19		2:45	4.16	15:06	4.38	8:46	1.41	21:19	1.21	2.75	3.17	2.96
31/07/19		3:35	4.39	15:54	4.64	9:35	1.18	22:08	0.94	3.21	3.70	3.46
01/08/19	N	4:23	4.59	16:41	4.85	10:22	0.98	22:55	0.73	3.61	4.12	3.87
02/08/19		5:10	4.72	17:27	4.98	11:08	0.84	23:42	0.63	3.88	4.35	4.12
03/08/19		5:57	4.76	18:15	5.01	11:55	0.80			3.96		3.96
04/08/19		6:44	4.70	19:03	4.91	0:29	0.64	12:42	0.85	4.06	4.06	4.06
05/08/19		7:32	4.55	19:54	4.71	1:17	0.79	13:31	1.00	3.76	3.71	3.74
06/08/19		8:24	4.34	20:47	4.44	2:07	1.02	14:23	1.23	3.32	3.21	3.27
07/08/19	C	9:20	4.11	21:47	4.14	3:00	1.31	15:19	1.48	2.80	2.66	2.73
08/08/19		10:23	3.92	22:56	3.89	3:58	1.60	16:24	1.72	2.32	2.17	2.25
09/08/19		11:35	3.82			5:05	1.81	17:38	1.86	2.01		2.01
10/08/19		0:14	3.76	12:48	3.83	6:19	1.90	18:55	1.86	1.86	1.97	1.92
11/08/19		1:29	3.76	13:53	3.94	7:28	1.86	20:01	1.75	1.90	2.19	2.05
12/08/19		2:29	3.85	14:45	4.10	8:25	1.74	20:54	1.59	2.11	2.51	2.31

13/08/19		3:16	3.98	15:28	4.26	9:11	1.59	21:38	1.43	2.39	2.83	2.61
14/08/19		3:55	4.10	16:06	4.39	9:51	1.45	22:16	1.30	2.65	3.09	2.87
15/08/19	LL	4:29	4.20	16:40	4.47	10:27	1.35	22:50	1.22	2.85	3.25	3.05
16/08/19		5:00	4.26	17:12	4.52	11:01	1.29	23:23	1.19	2.97	3.33	3.15
17/08/19		5:30	4.28	17:43	4.51	11:33	1.28	23:54	1.21	3.00	3.30	3.15
18/08/19		6:00	4.26	18:14	4.47			12:05	1.32		3.15	3.15
19/08/19		6:30	4.21	18:46	4.38	0:25	1.27	12:36	1.40	2.94	2.98	2.96
20/08/19		7:01	4.13	19:20	4.25	0:56	1.37	13:09	1.51	2.76	2.74	2.75
21/08/19		7:36	4.02	19:58	4.09	1:30	1.51	13:45	1.65	2.51	2.44	2.48
22/08/19		8:16	3.89	20:42	3.91	2:07	1.67	14:26	1.81	2.22	2.10	2.16
23/08/19	M	9:05	3.76	21:38	3.75	2:51	1.83	15:18	1.97	1.93	1.78	1.86
24/08/19		10:11	3.66	22:51	3.65	3:47	1.98	16:26	2.07	1.68	1.58	1.63
25/08/19		11:31	3.68			4:59	2.05	17:49	2.04	1.63		1.63
26/08/19		0:16	3.69	12:50	3.83	6:20	1.98	19:07	1.84	1.71	1.99	1.85
27/08/19		1:30	3.88	13:55	4.11	7:31	1.77	20:11	1.52	2.11	2.59	2.35
28/08/19		2:30	4.17	14:49	4.44	8:29	1.47	21:04	1.17	2.70	3.27	2.99
29/08/19		3:21	4.47	15:38	4.77	9:19	1.16	21:52	0.84	3.31	3.93	3.62
30/08/19	N	4:07	4.73	16:25	5.03	10:06	0.89	22:38	0.60	3.84	4.43	4.14
31/08/19		4:52	4.89	17:10	5.18	10:51	0.71	23:23	0.50	4.18	4.68	4.43
01/09/19		5:37	4.95	17:55	5.18	11:36	0.65			4.30		4.30
02/09/19		6:21	4.88	18:41	5.04	0:07	0.56	12:21	0.72	4.32	4.32	4.32
03/09/19		7:05	4.70	19:28	4.77	0:52	0.75	13:07	0.92	3.95	3.85	3.90
04/09/19		7:52	4.45	20:17	4.42	1:37	1.06	13:55	1.21	3.39	3.21	3.30
05/09/19		8:44	4.17	21:14	4.05	2:26	1.41	14:49	1.54	2.76	2.51	2.64
06/09/19	C	9:46	3.92	22:24	3.75	3:22	1.76	15:53	1.84	2.16	1.91	2.04
07/09/19		11:03	3.76	23:53	3.59	4:30	2.03	17:12	2.04	1.73	1.55	1.64
08/09/19				12:26	3.75	5:53	2.14	18:39	2.04		1.71	1.71
09/09/19		1:16	3.63	13:36	3.88	7:11	2.07	19:49	1.89	1.56	1.99	1.78
10/09/19		2:16	3.79	14:28	4.07	8:10	1.89	20:40	1.70	1.90	2.37	2.14
11/09/19		3:00	3.96	15:10	4.25	8:54	1.69	21:20	1.51	2.27	2.74	2.51
12/09/19		3:35	4.13	15:45	4.40	9:31	1.51	21:54	1.35	2.62	3.05	2.84
13/09/19		4:06	4.26	16:16	4.52	10:05	1.37	22:25	1.24	2.89	3.28	3.09
14/09/19	LL	4:35	4.36	16:46	4.59	10:37	1.28	22:55	1.19	3.08	3.40	3.24
15/09/19		5:02	4.42	17:16	4.61	11:07	1.25	23:24	1.18	3.17	3.43	3.30
16/09/19		5:30	4.43	17:45	4.59	11:36	1.26	23:53	1.22	3.17	3.37	3.27
17/09/19		5:58	4.41	18:16	4.51			12:06	1.32		3.19	3.19
18/09/19		6:29	4.33	18:48	4.38	0:22	1.31	12:37	1.42	3.02	2.96	2.99
19/09/19		7:01	4.22	19:24	4.21	0:54	1.45	13:12	1.57	2.77	2.64	2.71

20/09/19		7:39	4.07	20:06	4.00	1:30	1.62	13:53	1.74	2.45	2.26	2.36
21/09/19		8:26	3.91	21:01	3.79	2:13	1.82	14:44	1.93	2.09	1.86	1.98
22/09/19	M	9:31	3.76	22:20	3.65	3:08	2.02	15:53	2.07	1.74	1.58	1.66
23/09/19		10:59	3.72	23:56	3.68	4:24	2.14	17:23	2.06	1.58	1.62	1.60
24/09/19				12:28	3.88	5:55	2.08	18:49	1.84		2.04	2.04
25/09/19		1:15	3.92	13:37	4.19	7:13	1.83	19:54	1.50	2.09	2.69	2.39
26/09/19		2:14	4.24	14:32	4.55	8:11	1.48	20:46	1.12	2.76	3.43	3.10
27/09/19		3:03	4.57	15:20	4.88	9:01	1.14	21:33	0.80	3.43	4.08	3.76
28/09/19	N	3:48	4.84	16:06	5.13	9:47	0.85	22:17	0.59	3.99	4.54	4.27
29/09/19		4:31	5.01	16:49	5.25	10:31	0.67	23:00	0.53	4.34	4.72	4.53
30/09/19		5:13	5.05	17:33	5.21	11:14	0.63	23:42	0.63	4.42	4.58	4.50
01/10/19		5:55	4.97	18:16	5.02	11:58	0.73			4.24		4.24
02/10/19		6:37	4.78	19:00	4.71	0:24	0.86	12:42	0.96	3.92	3.75	3.84
03/10/19		7:21	4.52	19:47	4.34	1:07	1.19	13:29	1.28	3.33	3.06	3.20
04/10/19		8:10	4.22	20:41	3.96	1:53	1.55	14:21	1.63	2.67	2.33	2.50
05/10/19	C	9:09	3.95	21:51	3.66	2:46	1.91	15:23	1.95	2.04	1.71	1.88
06/10/19		10:26	3.76	23:23	3.52	3:54	2.18	16:43	2.14	1.58	1.38	1.48
07/10/19		11:53	3.73			5:21	2.29	18:13	2.14	1.44		1.44
08/10/19		0:51	3.58	13:07	3.84	6:45	2.20	19:23	1.99	1.38	1.85	1.62
09/10/19		1:51	3.76	14:00	4.03	7:44	2.01	20:13	1.79	1.75	2.24	2.00
10/10/19		2:33	3.95	14:42	4.21	8:29	1.79	20:52	1.60	2.16	2.61	2.39
11/10/19		3:07	4.14	15:16	4.38	9:05	1.60	21:25	1.43	2.54	2.95	2.75
12/10/19		3:37	4.30	15:48	4.52	9:38	1.44	21:56	1.30	2.86	3.22	3.04
13/10/19	LL	4:05	4.43	16:18	4.61	10:09	1.33	22:25	1.23	3.10	3.38	3.24
14/10/19		4:33	4.52	16:47	4.65	10:39	1.26	22:53	1.20	3.26	3.45	3.36
15/10/19		5:01	4.56	17:17	4.64	11:08	1.24	23:22	1.22	3.32	3.42	3.37
16/10/19		5:30	4.56	17:49	4.57	11:39	1.28	23:53	1.30	3.28	3.27	3.28
17/10/19		6:01	4.50	18:22	4.45			12:12	1.36		3.09	3.09
18/10/19		6:35	4.39	19:00	4.27	0:26	1.43	12:49	1.50	2.96	2.77	2.87
19/10/19		7:15	4.23	19:45	4.05	1:04	1.60	13:32	1.68	2.63	2.37	2.50
20/10/19		8:04	4.05	20:44	3.83	1:49	1.82	14:25	1.86	2.23	1.97	2.10
21/10/19	M	9:11	3.89	22:06	3.70	2:47	2.02	15:37	2.00	1.87	1.70	1.79
22/10/19		10:39	3.84	23:40	3.75	4:05	2.14	17:06	1.99	1.70	1.76	1.73
23/10/19				12:07	3.99	5:35	2.07	18:29	1.78		2.21	2.21
24/10/19		0:56	3.99	13:17	4.27	6:52	1.82	19:33	1.46	2.17	2.81	2.49
25/10/19		1:54	4.30	14:12	4.60	7:51	1.49	20:25	1.13	2.81	3.47	3.14
26/10/19		2:43	4.60	15:01	4.88	8:40	1.16	21:11	0.87	3.44	4.01	3.73
27/10/19		3:27	4.84	15:46	5.07	9:26	0.91	21:55	0.72	3.93	4.35	4.14

28/10/19	N	4:09	4.99	16:29	5.13	10:10	0.76	22:37	0.70	4.23	4.43	4.33
29/10/19		4:50	5.02	17:12	5.05	10:54	0.74	23:18	0.82	4.28	4.23	4.26
30/10/19		5:31	4.95	17:54	4.85	11:37	0.85	23:59	1.04	4.10	3.81	3.96
31/10/19		6:12	4.78	18:37	4.56			12:21	1.06		3.50	3.50
01/11/19		6:54	4.54	19:21	4.24	0:41	1.32	13:06	1.35	3.22	2.89	3.06
02/11/19		7:41	4.27	20:11	3.92	1:25	1.64	13:56	1.66	2.63	2.26	2.45
03/11/19		8:35	4.01	21:14	3.65	2:15	1.94	14:54	1.94	2.07	1.71	1.89
04/11/19	C	9:44	3.81	22:37	3.51	3:17	2.19	16:05	2.13	1.62	1.38	1.50
05/11/19		11:05	3.73			4:37	2.31	17:27	2.17	1.42		1.42
06/11/19		0:03	3.54	12:20	3.78	6:00	2.27	18:39	2.07	1.27	1.71	1.49
07/11/19		1:08	3.69	13:18	3.93	7:04	2.12	19:33	1.90	1.57	2.03	1.80
08/11/19		1:54	3.88	14:04	4.10	7:53	1.92	20:15	1.72	1.96	2.38	2.17
09/11/19		2:31	4.07	14:42	4.26	8:32	1.72	20:51	1.55	2.35	2.71	2.53
10/11/19		3:04	4.25	15:16	4.41	9:07	1.55	21:23	1.41	2.70	3.00	2.85
11/11/19		3:34	4.40	15:48	4.52	9:40	1.42	21:54	1.31	2.98	3.21	3.10
12/11/19	LL	4:05	4.53	16:21	4.59	10:12	1.31	22:24	1.24	3.22	3.35	3.29
13/11/19		4:35	4.61	16:54	4.61	10:44	1.25	22:56	1.23	3.36	3.38	3.37
14/11/19		5:07	4.63	17:28	4.57	11:18	1.25	23:30	1.28	3.38	3.29	3.34
15/11/19		5:42	4.60	18:06	4.46	11:55	1.29			3.31		3.31
16/11/19		6:20	4.51	18:48	4.31	0:07	1.38	12:36	1.39	3.13	2.92	3.03
17/11/19		7:03	4.37	19:37	4.11	0:48	1.54	13:22	1.54	2.83	2.57	2.70
18/11/19		7:56	4.20	20:38	3.93	1:37	1.72	14:18	1.70	2.48	2.23	2.36
19/11/19	M	9:02	4.06	21:55	3.82	2:37	1.90	15:27	1.81	2.16	2.01	2.09
20/11/19		10:22	4.01	23:18	3.85	3:50	2.00	16:46	1.81	2.01	2.04	2.03
21/11/19		11:43	4.09			5:11	1.96	18:03	1.68	2.13		2.13
22/11/19		0:31	4.02	12:52	4.28	6:25	1.77	19:08	1.46	2.25	2.82	2.54
23/11/19		1:30	4.26	13:50	4.50	7:26	1.52	20:02	1.24	2.74	3.26	3.00
24/11/19		2:21	4.50	14:41	4.69	8:19	1.27	20:50	1.06	3.23	3.63	3.43
25/11/19		3:07	4.69	15:28	4.81	9:07	1.07	21:34	0.96	3.62	3.85	3.74
26/11/19	N	3:50	4.82	16:12	4.83	9:53	0.95	22:17	0.96	3.87	3.87	3.87
27/11/19		4:31	4.86	16:55	4.76	10:37	0.93	22:58	1.03	3.93	3.73	3.83
28/11/19		5:12	4.82	17:36	4.61	11:21	1.00	23:38	1.18	3.82	3.43	3.63
29/11/19		5:52	4.71	18:18	4.41			12:04	1.15		3.26	3.26
30/11/19		6:34	4.54	19:00	4.17	0:19	1.38	12:48	1.36	3.16	2.81	2.99
01/12/19		7:17	4.32	19:44	3.94	1:02	1.61	13:34	1.59	2.71	2.35	2.53
02/12/19		8:05	4.11	20:36	3.73	1:48	1.84	14:23	1.81	2.27	1.92	2.10
03/12/19		9:00	3.91	21:38	3.58	2:40	2.04	15:21	1.99	1.87	1.59	1.73
04/12/19	C	10:04	3.78	22:52	3.52	3:44	2.19	16:27	2.10	1.59	1.42	1.51

05/12/19		11:15	3.73			4:57	2.25	17:37	2.10	1.48		1.48
06/12/19		0:04	3.58	12:21	3.79	6:07	2.19	18:39	2.01	1.39	1.78	1.59
07/12/19		1:01	3.72	13:16	3.90	7:05	2.05	19:29	1.87	1.67	2.03	1.85
08/12/19		1:48	3.90	14:02	4.05	7:52	1.88	20:12	1.71	2.02	2.34	2.18
09/12/19		2:27	4.09	14:43	4.20	8:33	1.70	20:49	1.55	2.39	2.65	2.52
10/12/19		3:03	4.27	15:20	4.34	9:11	1.53	21:24	1.41	2.74	2.93	2.84
11/12/19		3:38	4.43	15:58	4.45	9:47	1.38	21:59	1.30	3.05	3.15	3.10
12/12/19	LL	4:14	4.56	16:35	4.52	10:24	1.25	22:36	1.23	3.31	3.29	3.30
13/12/19		4:50	4.64	17:15	4.54	11:03	1.17	23:14	1.21	3.47	3.33	3.40
14/12/19		5:30	4.67	17:57	4.49	11:44	1.15	23:55	1.25	3.52	3.24	3.38
15/12/19		6:12	4.64	18:42	4.39			12:28	1.18		3.21	3.21
16/12/19		6:59	4.55	19:33	4.25	0:40	1.35	13:17	1.27	3.20	2.98	3.09
17/12/19		7:52	4.42	20:30	4.09	1:30	1.48	14:11	1.40	2.94	2.69	2.82
18/12/19		8:52	4.28	21:35	3.97	2:27	1.62	15:12	1.53	2.66	2.44	2.55
19/12/19	M	10:00	4.18	22:48	3.93	3:31	1.74	16:20	1.61	2.44	2.32	2.38
20/12/19		11:13	4.13	23:59	3.98	4:42	1.78	17:32	1.62	2.35	2.36	2.36
21/12/19				12:25	4.17	5:54	1.73	18:39	1.55		2.62	2.62
22/12/19		1:03	4.11	13:29	4.26	7:01	1.61	19:39	1.45	2.50	2.81	2.66
23/12/19		2:00	4.27	14:26	4.36	8:00	1.45	20:31	1.33	2.82	3.03	2.93
24/12/19		2:50	4.43	15:16	4.44	8:53	1.29	21:18	1.24	3.14	3.20	3.17
25/12/19		3:36	4.56	16:02	4.48	9:41	1.17	22:02	1.19	3.39	3.29	3.34
26/12/19	N	4:19	4.64	16:44	4.47	10:26	1.11	22:43	1.19	3.53	3.28	3.41
27/12/19		4:59	4.66	17:24	4.41	11:09	1.10	23:23	1.24	3.56	3.17	3.37
28/12/19		5:38	4.62	18:02	4.30	11:50	1.16			3.46		3.46
29/12/19		6:17	4.53	18:39	4.17	0:02	1.33	12:30	1.28	3.20	2.89	3.05
30/12/19		6:55	4.39	19:17	4.02	0:42	1.46	13:10	1.43	2.93	2.59	2.76
31/12/19		7:35	4.23	19:57	3.86	1:22	1.62	13:51	1.60	2.61	2.26	2.44

Table 1: Tide table of 2019 for Santander. Source: Port Authority of Santander.

.4 Wave rose for 2010 - 2020

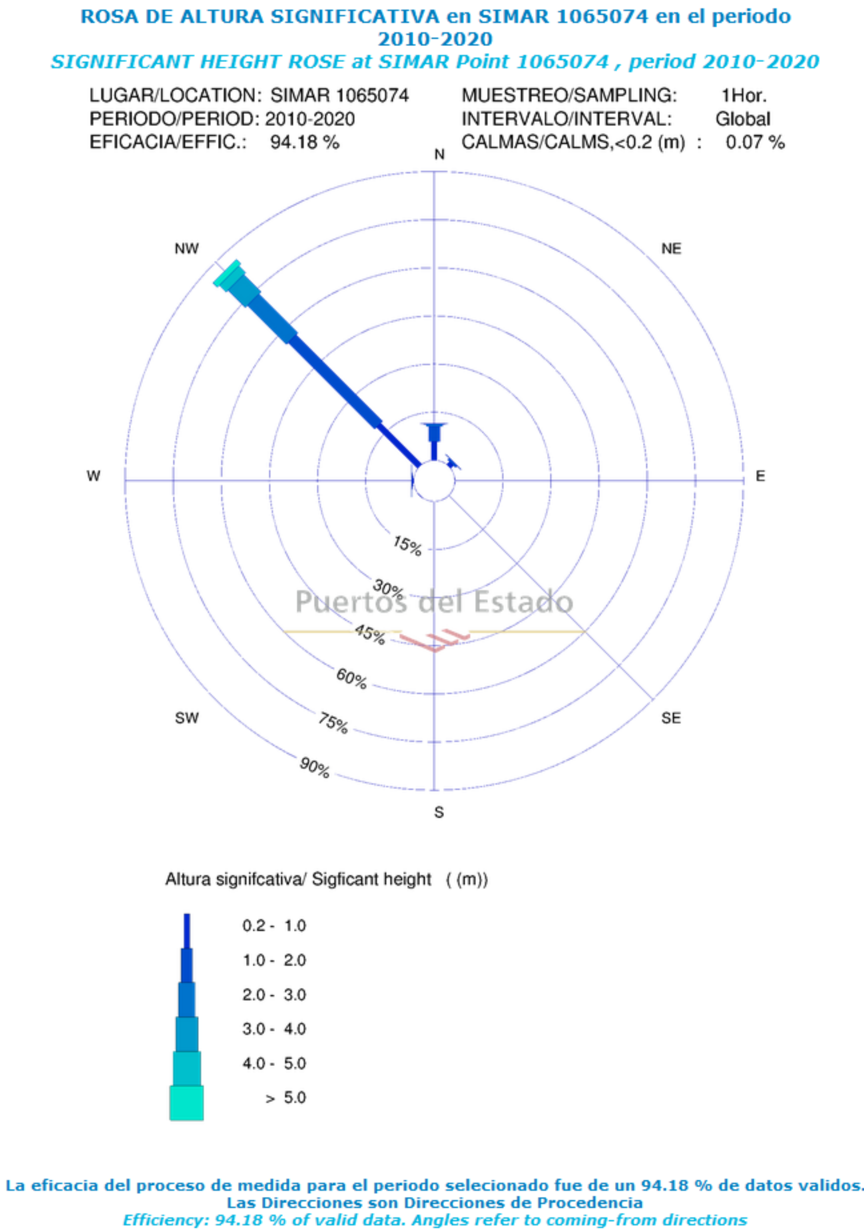


Figure 25: Wave rose for the Santander's port summarizing the wave height and direction between 2010 - 2020. Source: Puertos del Estado [43].