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## **Master's Thesis**

# **Systematic Design of a Composite Tidal Turbine Blade and Evaluation of Tidal Energy Based on Ecologic and Economic Factors**

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## Master's Thesis, Diploma Thesis

### Systematic design of a composite tidal turbine blade and evaluation of tidal energy based on ecologic and economic factors.

Tidal power plants have the potential to play an important role in the world's renewable energy supply. Worldwide a potential for energy generation of up to 3.800 TWh/a is assumed to be available for future tidal current power plants. To leverage these immense resources there is a strong need for research and basic technological developments. The technological feasibility of harvesting tidal current energy at large scale is being developed by several projects and companies, but still has significant technical and economic challenges to be overcome before there will be a wide-scale application. The future facilities have to be more efficient, robust and affordable and have to operate for a long time reliably in a rough environment. Key components of the whole plant are the turbine blades that are preferably realized using composite materials.

The goal of this thesis is the design of a composite tidal turbine blade using with input (flow speeds, target diameter) from our partner in Singapore. The design will be done using open source design software (e.g. Harp\_Opt [https://nwtc.nrel.gov/HARP\\_Opt](https://nwtc.nrel.gov/HARP_Opt) or QBlade <http://www.q-blade.org>). In addition a comparison of tidal energy to other established and renewable energy sources and an evaluation based on ecologic and economic factors will be done.

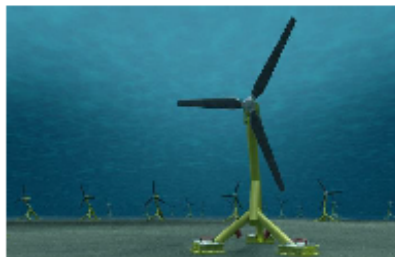


Figure: Array of tidal turbines under sea [Andritz Hydro]

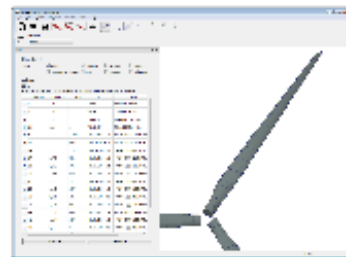


Figure: Blade design software [QBlade]

#### Research focus of the thesis

- Literature review on blade design and the available open source design software
- Design of a tidal turbine blade based on specific input factors
- Literature review on tidal energy and energy sources
- Evaluation of tidal energy compared to other energy sources
- Detailed documentation of the entire work in English

#### Requirements

- Independent and motivated way of working
- Basic knowledge on composite materials and product development methods

**Starting date:** March 2016

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## Übersicht

Energieerzeugung ist heutzutage immer noch stark von fossilen Brennstoffen abhängig, auch wenn sie negative Auswirkungen auf die Umwelt haben und ihre Ressourcen begrenzt sind. Erneuerbare Energien werden jetzt im Energiemarkt eingeführt, aber weitere Verbesserungen sind in diesem Bereich noch notwendig. Die Gezeitenenergie hat zum Vorteil, dass sie sehr planbar ist. Jedoch steht die Technologie noch am Anfang ihrer Entwicklung. Zur Beurteilung der positiven Effekte dieser Technologie wurde eine Literaturrecherche durchgeführt, und daraus die Kosten für die Energie (COE) und die Emission von Treibhausgasen (GHG) durch den gesamten Lebenszyklus bewertet. Diese Werte wurden mit den COE und GHG-Emissionen anderer Energiequellen verglichen. Die Ergebnisse zeigten, dass die Gezeitenenergie wirtschaftlich rentabel sein könnte, wenn sie richtig entwickelt wäre. Bisher sind die einmaligen Anschaffungskosten zu hoch. Eine der besonderen Herausforderungen der Gezeitenenergie ist die Entwicklung geeigneter Fertigungsverfahren für die einzelnen Bauteile. Um dieses Problem zu beheben, wurde ein Blatt für eine Turbine mit Open-Source Software (*QBlade* und *HARP\_Opt*) entwickelt. Das Blatt wird im Rahmen zukünftiger Arbeiten übernommen, um die Anforderungen an die Fertigungsverfahren abzuleiten.

## Abstract

Energy generation nowadays is still highly dependent on fossil fuels, even though they have adverse environmental impact and their resources are limited. Renewable energy technologies are starting to be introduced in the energy market but further improvements are still needed in that field. Among them, tidal energy has the advantage of being highly predictable. However, it is still in its infancy. To assess whether it is worth to develop this kind of technology, a literature search has been conducted to evaluate the cost of energy (COE) and the emission of greenhouse-gases (GHG) through the whole life-cycle. These values have been compared with the COE and GHG emissions for other sources of energy. Results show that tidal energy can be economically feasible if it were properly developed since its cost is mainly driven by initial capital expenditures. One of the specific identified challenges for its deployment is the establishment of suitable manufacturing methods. To address this issue, a blade for a tidal turbine has been designed using open-source software (*QBlade* and *HARP\_Opt*). The blade will be subject to future studies in order to derive manufacturing requirements and constraints.

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## Nomenklatur

| Symbol | Unit               | Description                        |
|--------|--------------------|------------------------------------|
| $A$    | $m^2$              | Area                               |
| $C_p$  | -                  | Power coefficient                  |
| $E$    | Pa                 | Elasticity module                  |
| $n$    | year               | Time                               |
| $P$    | W                  | Power                              |
| $Q_n$  | Wh                 | Energy output on year $n$          |
| rpm    | -                  | Revolutions per minute             |
| $V$    | m/s                | Velocity                           |
| $x$    | m                  | Spanwise location of blade segment |
| $y$    | m                  | Distance to blade root             |
| ¢      | Cents of US Dollar | Currency                           |
| €      | Euro               | Currency                           |
| \$     | US Dollar          | Currency                           |
| $\rho$ | $kg/m^3$           | Density                            |

## List of abbreviations

|      |  |
|------|--|
| AEP  | Annual Energy Production               |
| AoA  | Angle of Attack                        |
| BEM  | Blade-Element Theory Momentum          |
| COE  | Cost of Energy                         |
| GHG  | Greenhouse-gas (es)                    |
| IEA  | International Energy Agency            |
| LCA  | Life-Cycle Approach                    |
| LCOE | Levelized Cost of Energy               |
| Mtoe | Million Tons of Oil Equivalent         |
| NREL | National Renewable Energies Laboratory |
| PV   | Photovoltaic                           |
| RET  | Renewable Energy Technology(ies)       |
| TLCC | Total Life-Cycle Cost                  |
| TCT  | Tidal Current Turbine                  |



# 1 Introduction

This initial chapter presents a global overview of the thesis. First of all, the motivation for this research will be argued, stating the specific objectives and goals proposed for this work. Consequently, the research design will be given, which present how those goals will be achieved.

## 1.1 Motivation and Objectives

The world's population is constantly increasing, along with people's energy consumption, which makes energy demand grow incessantly. One of the reasons for this growth is the expansion of some emerging countries and their economies. Nowadays, the energy supply is mainly dependent on fossil fuels. However, this dependence is becoming concerning, since these fuels have some serious consequences, like climate change and eventually the depletion of their reserves [1]. Therefore, there is an emerging need for new energy sources and technologies to replace them, in order to secure the energy supply in a more eco-friendly way.

In this context is where renewable energy technologies (RET) gain importance. Renewable energy sources are those that can be constantly recovered by nature (e.g. biomass, hydropower, wind power, sun, geothermal, marine energies...). Technically, they have the potential to cover all global energy demand [2]. The use of these technologies has some clear advantages over conventional fossil fuels. First of all, they can provide energy with zero or almost zero emissions of both air pollutants and greenhouse gases (GHG) [3]. Also, their renewable character makes them an inexhaustible energy source. Thus, they seem to be a good choice for responding to the energy demand.

However, renewable energy sources have a main drawback that is their variability. This generates the need of storage or backup power, which increases significantly the capital costs [4], hindering their complete deployment and achievement of competitive prices. In this context, there is one renewable energy source that does not have this problem: tidal energy. This presents an opportunity to ensure a higher security in energy supply while reducing the GHG emissions [5]. But so far, river and tidal current hydrokinetic systems are still in the early phases of their development [6].

With the purpose of contributing to the development of tidal energy system, this thesis has two different though related goals:

- (1) **Evaluate tidal energy in a systematic way taking into account different factors of influence.** The aim of this evaluation is to obtain an overview about tidal energy compared to the other exploited energy sources, and try to assess what technology is worth what, or if tidal energy is a good alternative energy source and why. More specifically, this thesis will try to answer the following aspects:
  - How can an energy source be evaluated and compared among others?
  - What aspects of an energy source are of importance and should therefore be taken into account?
  - Are there existing studies in the literature assessing said aspects?
- (2) **Design a blade for a tidal turbine to infer manufacturing requirements and constraints.**
  - What is the goal of this design?
  - What software can be used design a turbine blade and why?
  - What input is needed to develop a tidal turbine blade?

## 1.2 Research Design

This thesis has two main goals, as previously explained. But to begin with, **what is the need for tidal energy?** The following chapter, the State of the Art, will present the current status of the energy share in the world energy consumption. It shows which are the most used energy sources, and divides them according to whether they are renewable or not. As can be seen in Figure 1, this is the first step of the thesis. From there, two different paths are followed.

One of them is a **theoretical evaluation of tidal energy**. This part of the thesis is pictured in the left side of Figure 1. Its aim is to present the results of an evaluation of tidal energy regarding economic and ecological factors. As can be seen in Figure 1, this evaluation encloses several steps. First of all, **how can an energy source be evaluated and compared with others?** The easiest way is to choose specific factors to evaluate them, and thus compare these numerical factors between the different sources. But **what aspects of an energy source should be taken into account?** It makes sense to assess the economic viability of an energy technology, as well as its environmental suitability, since it is one of the main global current concerns. To conduct this evaluation, the literature has been reviewed, and a specific parameter to evaluate each of these aspects has been chosen. As shown in Figure 1, the economic comparison will be made evaluating the **Levelized Cost of Energy (LCOE)** for every energy source. The environmental comparison will be made accounting for the **GHG emissions** produced by them.

The other part of this thesis, shown in the right side of Figure 1, involves the **design of a tidal turbine blade**. Once again, more than one step have been performed to achieve this target. In order to properly develop this design, it has to be stated **what is the purpose of designing the blade**. In Figure 1 this is put as Goal definition. In this thesis, the purpose of designing a blade is to extract what would be the requirements or restrictions regarding its manufacturing process. From there, it has to be chosen **what software will be used to develop the blade**. Some suitable programs will be considered to that end, and regarding the purpose of this design a specific approach to designing the blade will be defined. Finally, with the needed input, the **blade design** will be performed and utterly described.

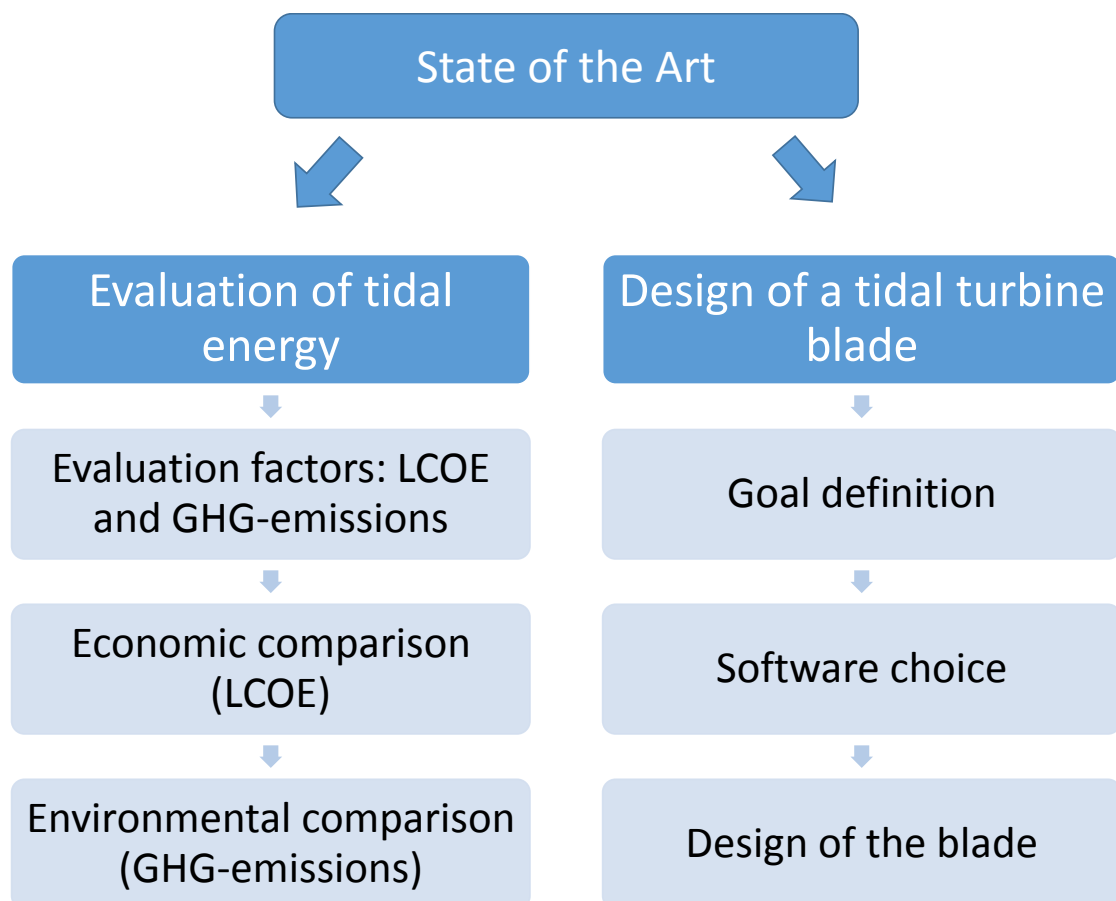


Figure 1: Structure of the thesis

## 2 State of the Art

Energy is crucial for economic growth and improvement of quality of life [7]. It can be found and used in many forms (e.g. electricity, heating, transportation) and it is needed to provide most services of modern society [8]. In addition, the increasing Earth's population causes a constant growth in energy demand. Therefore, ensuring energy supply is a global issue: there is an overall concern about how to meet this growing energy demand in the long term.

Energy supply depends on the energy sources that are available in our planet, and our ability to exploit them. This chapter presents the world energy consumption, and briefly introduces the most common energy sources. These are mostly conventional energy sources, based on oil, coal and natural gas [9] as well as nuclear power and some renewable energies.

### 2.1 World Energy Share

The total primary energy supply in 2013 was 13,541 million tons of oil equivalent (mtoe) [10]. This energy is provided by different energy source or fuels. Figure 2 shows what share of this amount is provided by each source. In it, the share corresponding to *Others* refers to other sources of energy such as geothermal, wind or solar.

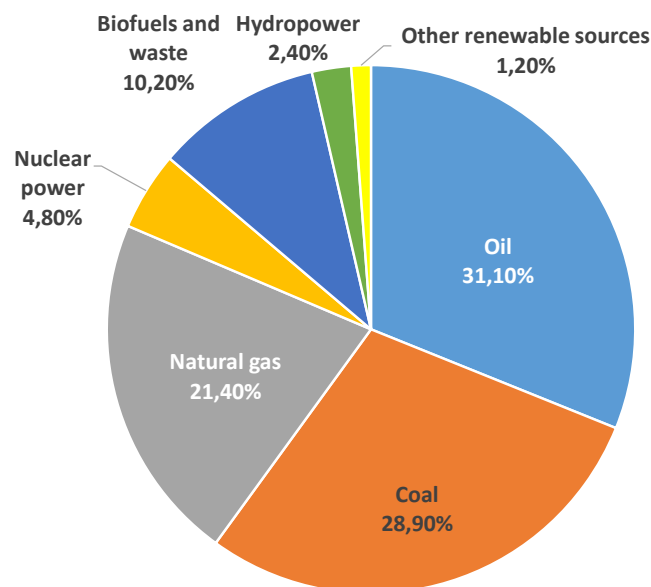


Figure 2: World Energy Share by Fuel in 2013 [10]

Energy sources can be classified into three areas: **fossil fuels** (oil, coal and gas), **nuclear power and renewable energy technologies** (hydropower, biomass, geothermal, wind, etc.). The bulk of the energy supply, **more than an 80%, is carried by fossil fuels** (see Figure 2). They have been the main source of energy supply for thousands of years, evolving to refined liquid phases (oil) and gaseous phases (gas) over time [11]. However, some

renewable energy sources have also been present for a long time, such as biomass, hydropower and wind energy. Most recently, nuclear power has also penetrated the energy market.

According to the International Energy Agency, approximately 18% of the world's energy consumption is in form of electricity (around 23300 TWh). The sources of electricity production are shown in Figure 3, with its respective shares. The share of nuclear power and renewable energy technologies is now higher than in the global energy consumption, since most of their resources are used to this end. Instead, share of oil is lower, because it is mainly used in the transportation sector [8].

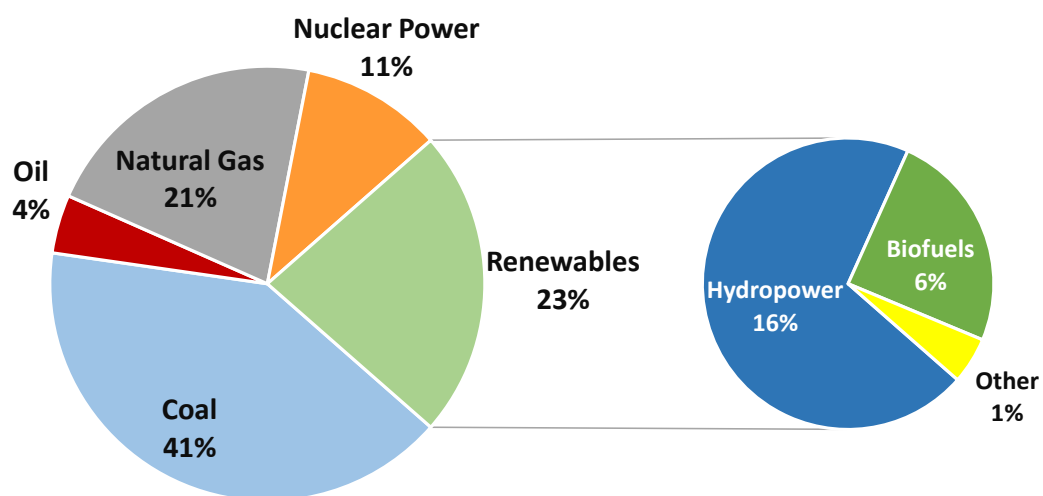


Figure 3: Fuel Shares of Electricity Generation in 2013 [10]

Within the share of renewables in electricity production, the main source is hydropower (up to 70% of the renewable energy sources). *Other* renewable energy technologies refers to other such as geothermal, wind or solar.

A heavy dependence on fossil fuels can be seen in the electricity generation share. These are still the most important sources of world's primary energy supply [11]. The utilization of fossil fuels has some advantages, like cheap energy production. But the reliance on this energy sources leads to some major concerns. On the one hand, **fossil fuels have a limited potential**: there is only a finite amount of fossil fuels available on Earth. At the current rate of exploitation, this resources will most likely deplete in the next decades [7,8,12,13]. On the other hand, **their combustion produces exhaust emissions**, such as carbon dioxide (CO<sub>2</sub>), which are dangerous to human health and the environment, causing global warming through the so-called greenhouse-effect: the gases released into the atmosphere prevent the Earth

from radiating the heat from the Sun back to space. This causes a rise in the global temperature, and consequently climate changes [8,9,12,14,15].

In conclusion, it looks like energy demand will continue to increase in the next decades but the traditional sources of electricity generation are either limited or environmentally threatening. Consequently, renewable energy technologies have emerged as a response to the need of new sustainable energy resources. This categorization of sources regards their sustainability: non-renewable resources are those who cannot be replaced by natural means at the same rate of consumption. Based on this differentiation, the following sub-sections take a deeper look into different energy sources present in the energy share.

### 2.1.1 Non-Renewable Energy Sources

Non-renewable energy sources are those **resources in Earth that once consumed cannot be immediately replaced**. That implies that their resource is limited. Therefore, the current dependence on them will threaten the security of supply in the near future.

From the energy shares shown above, fossil fuels are clearly predominant in the energy market: oil (including liquid fuels and petroleum), coal and natural gas. For many years, these sources have been the driving force of society and have hugely improved human quality of life, i.e. through enabling the development of science, technology and knowledge [13]. Modern society is a consequence of the exploitation of fossil fuels. But since these fuels are non-renewable sources, they will eventually deplete. More specifically, it might happen in the near future at current energy consumption and exploitation rates.

In addition, energy generation from fossil fuels has some major negative consequences, basically due to the **emission of gases** and **waste heat from combustion**. Waste heat can be partly reused through recovery systems such as regenerators, economizers or heat pumps. But greenhouse gas emissions cause mainly two issues. On the one hand, they contribute to **air pollution**, which is damaging to human health. On the other hand, they have **direct impact on the environment**. Even though climate on Earth is always changing [13], but it is believed that human activity is contributing to global warming.

Apart from their combustion, fossil fuels have also ecological consequences during other stages of the energy production. The whole life-cycle of energy generation through fossil fuels consists in exploration and extraction, transportation, refining (if needed) and electricity generation. The latter involves the construction of a power plant, its operation and maintenance, and posterior ash disposal in the case of coal-fired plants.

Apart from fossil fuels, nuclear power is also emerging as an energy source. Even though its share is relatively lower, it has also been included in this section together with fossil fuels since it is also a non-renewable resource. A

brief explanation for each of them is given below: a short description and their common uses.

### 2.1.1.1 Oil

Fuel known as crude oil is a liquid that can vary from a light-brown colour to a highly viscous tar-like fluid. It is in liquid phase under atmospheric or standard conditions [8]. It is composed of a complex mixture of oxygenated hydrocarbons, but may also contain sulphur, nitrogen and metallic compounds [7]. These hydrocarbon accumulations are found in under-surface basins that satisfy a set of conditions (e.g. geological and organic composition, temperature). Due to high temperature and pressure, oil might contain some dissolved gas, which will be released when oil is brought to the surface [8]. Heat value of oil and its products is normally between 40 and 44 MJ/kg [16].

Crude oil is processed in several steps before being distributed as the desired product, e.g. gasoline or diesel. It can be stored and its energy produced when needed. That is why it is widely used in the transportation sector. In general, it is mostly consumed as a source of energy, even though some of its refined products are also used as components to manufacturing plastics, fibres, candles, etc.

The **resources-to-production ratio** is an indicator for the security of supply of non-renewable energy sources [17]. This ratio gives a hint of how many years of production are left for a specific fuel at the current production rate [18]. This value is constantly changing, but it implies the imminent need of finding new energy resources. According to [19], resources-to-production ratio for oil is around 40. Even though its demand is still increasing, the consumption is expected to slowly be reduced pushed by the development of renewables or use of oil substitutes such as gas.

### 2.1.1.2 Natural Gas

Natural gas is colourless and odourless in its pure form, composed of inorganic gases and saturated hydrocarbons. It is found together with oil under Earth's surface in petroleum reservoirs. It is combustible, giving off a large quantity of energy. But it has lower emissions of CO<sub>2</sub> than coal or oil for equivalent energy produced [7]. Heat value for natural gas is around 38 and 45 MJ/kg [16], depending on the site of extraction.

Since natural gas is not available everywhere, it has to be transported from the extraction site. Nowadays this can be made through onshore or offshore pipelines, or liquefying the gas before its transportation, which is economically more profitable for long distances.

Almost all of the extracted gas is used to electricity production in power plants, or for heating and cooking purposes. Unlike oil, a very small share is used for transportation. Capital costs and construction times for gas-fired power plants

are relatively low [8]. Also, these plants have high flexibility and efficiency levels. These factors together with the low emissions makes natural gas a highly attractive fuel for plant operators, investors and governments [8]. That is most likely why consumption has increased almost four times in the last 50 years [7].

Nowadays, the resources-to-production ratio for natural gas is around 60, and is slightly increasing. According to [19] there will be enough gas for the next decade, even though it is inevitable its eventual depletion.

### **2.1.1.3 Coal**

Coal is the most abundant fossil fuel, and cheaper and easier to explore than e.g. oil or natural gas. Even its abundance, its resources-to-production ratio for coal was about 150 in 2005 according to [19].

Coal consists in carbon agglomerations with variable quantities of other elements, e.g. hydrogen, oxygen, etc. It is produced through the natural process of carbonization, similar to that responsible of oil and gas formation: organic matter subjected to specific high temperatures and pressures, protected from biodegradation and oxidation by mud or acidic water is transformed into peat and then coal through physical and chemical changes. There are different types of coal depending on the age and depth of the reservoir, varying also their qualities and heating values [8].

Coal is mostly used for electricity generation in power plants. This process involves the combustion of the fuel, which releases heat of the order of 20 or 30 MJ/kg [8,16]. Typical ranges for power plants are 500 to 1000 MW by burning 250 to 500 tonnes of coal per hour [8].

At the moment, coal is the one of the cheapest electricity generation technologies. Capital costs are relatively low, which is why coal-firing is relatively popular in developing countries. But this might change in the near future, since carbon emissions are particularly abundant and could cause new environmental regulations to emerge [8].

### **2.1.1.4 Nuclear Power**

Nuclear power is the last non-renewable source most used for electricity generation. As shown in Figure 3, it accounts for 21% of electricity generation. Atomic nucleus have been studied since 1930, and the first nuclear reactors were generating power for the grid before 1960 [8].

Energy can be obtained from atomic nuclei through the processes of fission or fusion, which take place in a nuclear reactor. These processes release a large amount of energy (of the magnitude of 200 MeV) compared to e.g. coal-firing releases a few eV per event [8]. Unlike burning fossil fuels, these nuclear reactions do not lead to the emissions of greenhouse gases [7], even less than

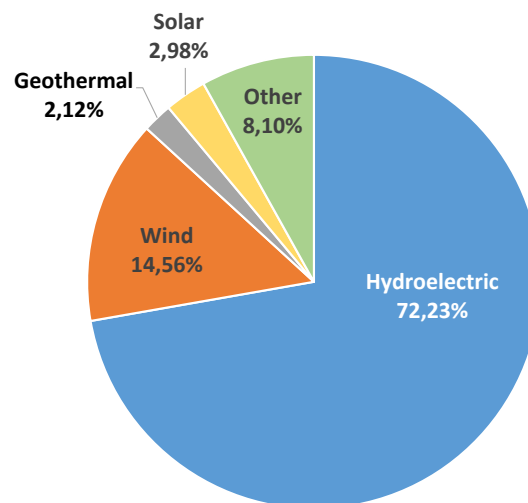


wind power or solar power generation [19]. In conclusion, nuclear plants are clean and efficient to operate in comparison with many other technologies.

However, nuclear power generation has other environmental impacts. Reactive gases are released during the reaction, which must be contained within the reactor during the operation of the plant. Also the mining and manipulation of the fuel (e.g. uranium) involves risks like radiation leaks. Finally, storage of spent radioactive fuel, which is toxic, is another concern [11]. That is why there has always been some scepticism towards the construction and operation of nuclear reactors [8].

### 2.1.2 Renewable Energy Sources

The previous section has offered a brief introduction to conventional energy sources, giving an overview on the scarcity of resources and the consequences of their use. The following step is to look for new energy sources available on Earth that could eventually replace fossil fuels.



**Figure 4: World Energy Shares of Electricity Productions with Renewable Energy Sources [7]**

Renewable energy resources can be recovered in a measurable period of time [1], making them more suitable for a long-term employment. They offer a higher potential than their actual energy production [7], since they are abundant in nature and widely available [20]. And most important, they offer a clean alternative to produce energy: they use indigenous resources, and provide with almost zero emissions of both pollutants and GHG [11].

But nowadays, economic barriers are the main impediment to a higher deployment of renewable technologies. The goal for renewable energies is to achieve 'grid parity', which means that their lifetime generation costs are comparable with the electricity prices, in order to compete in costs with other energy sources already present in the grid [21].

Consequently, renewable energy technologies are being developed and are gradually penetrating the energy market. Nowadays they provide more than 20% of the electricity generated worldwide. The following sections present a brief description of the technologies and resources that provide most part of it.

### **2.1.2.1 Hydropower**

Hydropower is the most used renewable energy resource. Half of the installed capacity is in Europe and North America (where hydro plants are already set up in the best sites). But small, mini and micro hydro plants (10 MW, 2 MW and 100 kW) play also a key role in many rural areas of some countries [9].

The basic principle of hydropower is to extract power from falling water. That means transforming the kinetic energy of the running water into electricity, which causes a reduction in the velocity of the fluid. This can be done through three different systems: run of river; dam system and high lying reservoir [8]. All of them involve a turbine impulse by the flowing water.

This energy resource is usually conceived as emission-free. But that is only considering the generation of electricity alone. Taking into account the whole lifetime cycle of this process (construction of the plant, operation, decommissioning, etc.) there are several stages that can contribute to GHG emissions and other environmental damage. For example, their operation can involve environmental impacts such as destruction of river habitats, lower the quality of water and the spread water related diseases [9].

### **2.1.2.2 Wind Energy**

Wind energy is second generation solar energy, because wind is mainly caused by solar energy absorbed by the atmosphere. This creates temperature differences across the atmosphere, which combined with Earth's rotation cause circulation of air. Kinetic energy can be extracted from air analogously to hydropower: wind pushes rotor blades transferring its kinetic energy, making them rotate.

Wind energy is widely available and produces no pollution or exhaust gases during power generation, but there are some negative environmental aspects related to it [9]. These can be acoustic noise; visual impact in the landscape; electromagnetic interference with radio, TV and radar signals, or impact on bird's life. Noise and visual impact generate the greatest problems when finding a site for a wind farm [9].



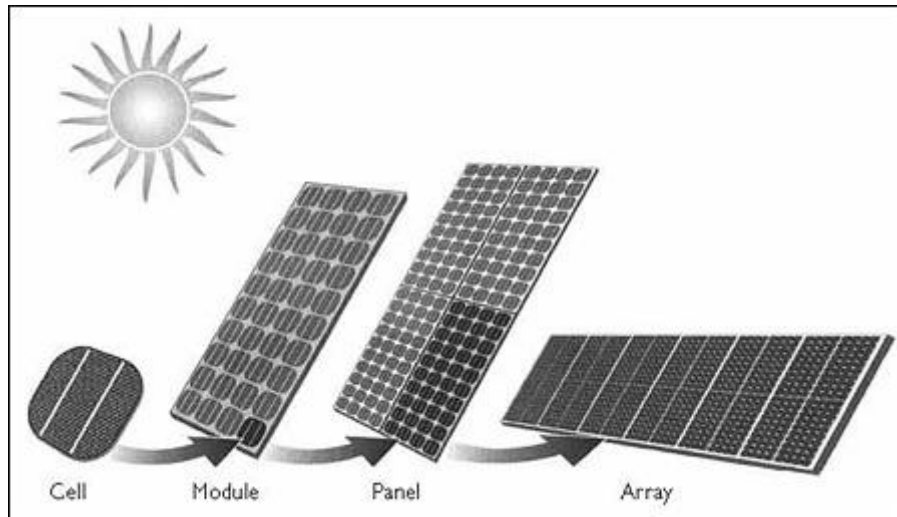
**Figure 5: Wind Energy Farm installed by Iberdrola SA [22]**

Advantages of wind energy over other energy sources (both fossil fuels and other renewables) are, for example, that it is modular. That means, new devices are easier and faster to install than other power plants. An example of a wind energy farm is shown in Figure 5. Also, reparations and maintenance do not require the whole plant to shut down, so the rest of the turbines can keep on generating [9].

### **2.1.2.3 Solar Energy**

Sunlight can be converted into energy through two different technologies: solar photovoltaic and solar thermal. Solar photovoltaic (PV) modules convert sunlight directly into electricity, while solar thermal power systems concentrate it to produce steam that generates electricity when going through a turbine.

Solar cells, made of semi-conductor material, are interconnected and sealed to constitute a module. A set of modules form a panel, which together with other components such as batteries constitute PV array systems and power plants (see Figure 6). Therefore, solar PV is modular by nature [20]. For proper utilization of PV technology, global solar radiation variation needs to be accurately known [23], since it is one of the main factors affecting PV efficiency and output.



**Figure 6: Solar PV System Components**

Solar PV is one of the fastest growing RETs in the world. From 2000 to 2010, global deployment has increased from 0.26 to 16.1 GW with an annual growth rate of more than 40%. This growth is due to both technological innovations that have reduced manufacturing costs by 100 times and various government incentives for consumers and producers [21]. But initial capital costs are relatively high, holding this technology back from being competitive. Therefore, it still has to achieve grid parity, which entails reducing the cost of solar PV electricity to be competitive with conventional grid supplied electricity [21].

#### **2.1.2.4 Biomass**

Biomass or biofuel refers to all organic material originating from plants (including algae), trees and crops. They are essentially the collection and storage of sun's energy through photosynthesis. It can be converted into useful forms of energy such as heat, electricity or liquid fuels [9]. It is probably the oldest energy source used by humans, and was dominant up to the 18<sup>th</sup> century, before the "fossil era" [8]. Traditional biomass is known as the direct use of biomass, which releases the necessary energy for cooking and heating, while modern biomass refers to its transformation into heat and electricity.

Biomass can be converted efficiently and cost-competitively into more convenient forms such as gases, liquids or electricity through three main processes [8]:

- Combustion, as a regular fuel, to obtain heat and electricity.
- Dry chemical processes (pyrolysis and gasification), to obtain other forms of fuel that can be transported and consumed when required, and have a higher calorific value.
- Aqueous processes, to obtain end products like oils, methane and ethanol.

Nowadays, biomass accounts for a low energy usage in developing countries. But it might play a much more significant role in the future if technologies that convert solid biomass into clean, convenient energy carriers were widely implemented. In countries where more supportive policies are applied, biomass contribution reaches between 10 and 20% (e.g. in Austria, Sweden or Finland) [9].

## 2.2 Tidal Energy

In this context of innovation challenge towards renewable energies, ocean energy has to be considered. Ocean energy can be exploited in order to obtain electricity from the kinetic energy enclosed in tidal currents and waves [1]. If properly harnessed, ocean energy provides an opportunity to ensure energy supply while reducing GHG emissions [5].

### 2.2.1 Tidal Power Background

Tidal power is **generated by the periodic variations of the gravitational attraction between the Earth, Moon and Sun** [1] (see Figure 7). The generated forces produce ocean currents: the sea level increases and then falls, moving the water towards the coast creating a tide. These tidal flows occur twice every about 24 hours, so they are **highly predictable** [24,25], which gives this resource a huge advantage over many other natural resources such as wind or sun. This predictability provides more certainty over the timing of power generation [24]. It also ensures quantifiable long-term energy yields that can be planned for and managed with the electrical grid [25].

Despite the advantages, tidal energy still has some obstacles or drawbacks to overcome to enable its exploitation. On the one hand, the access to such sites and devices (for both their installation and posterior maintenance and reparations) can represent an issue [26]. Also the proper installation is complex due to their underwater location: foundation or submarine cables establishment can result problematic [26]. Regarding the site, some locations have to be avoided due to leisure or commercial marine uses [24], so not all potential sites can be harvested. On the other hand, acceptable capital and operating costs is a also major challenge [24]. Special installations as the above mentioned (e.g. submarine cabling) are required, and they increase the capital costs. In addition, the environmental conditions are more severe than for wind turbines. The higher density of water causes a greater thrust to be generated. To resist this larger thrusts, a higher quantity of material, or a stronger one will be needed [26], which will also result in greater capital costs. Also the fluctuations in the flow velocity can lead to vibrations in the blade, that can eventually lead to fatigue failure of the material [26]. Issues about design and manufacturing also need to be addressed to make sure these requirements are fulfilled. Turbulence and cavitation effects should be taken into account when

configuring the blade, and manufacturing methods are not still optimized concerning tidal blades [26].

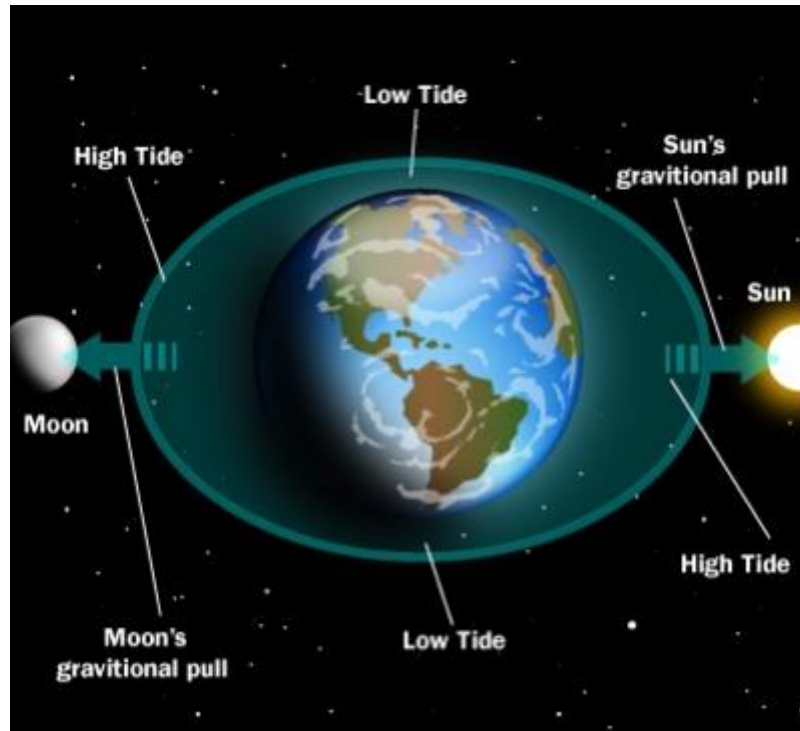


Figure 7: Ocean Tides Caused by Gravitational Forces

Regarding the extraction of power from the tide, there are two main methods [25]:

- (1) **Tidal barrages:** water is held behind a wall and then released in a controlled way through a typical hydropower plant constructed within the wall.
- (2) **Tidal current stream generators:** a set of hydrofoils generates a torque driving a generator when the water flow passes through. Unlike conventional hydropower, these are integrated in the tide so that they do not alter significantly the natural water stream [27].

Conventional hydropower is not sufficient to meet the increasing world's energy demand [6]. By developing and using tidal current turbines (TCT), the construction of dams or penstocks can be spared, which come with some environmental harm (e.g. submerging of agricultural lands). Instead, TCT's goal is to extract the energy from the moving fluid without having to retain or store it. environmental impact of TCT is believed to be minimal in comparison to tidal barrages [[26], since marine species are not commonly found in the sites in which these devices are normally located. However, the environmental impact of a specific installation should be assessed for each project.



Nevertheless, tidal barrages are currently a more developed and reliable technology than TCT. Numerous sites are being considered worldwide for development, and four tidal barrage power plants are currently in operation [26]:

- La Rance, France (see Figure 8).
- Annapolis Tidal Power Station, Bay of Fundy, Canada (see Figure 9).
- Kislaya Guba power facility, Russia.
- Jangxia Creek, East China Sea.



Figure 8: La Rance Tidal Barrage Plant, France

Meanwhile, most TCT technologies are **at proof-of-concept or research and development stage** [27]. The working principle of such devices can be strongly related to wind turbines, which also extract the kinetic energy from a moving fluid [28]. When the inflow water encounters the turbine, the generated hydrodynamic forces create a lift in the blades which is perpendicular to the rotor plane. These forces cause the blades to rotate, producing a torque that is transferred through the shaft and gearbox to the generator [5]. Consequently, the flow experiences a velocity loss when passing through the turbine, due to the energy captured by the turbine.



Figure 9: Annapolis Tidal Power Station, Canada

As well as for wind turbines, TCT are characterized by its axis' orientation (horizontal or vertical) and the number of blades. **Horizontal axis TCT** are those whose axis is parallel to the flow, while **vertical axis TCT** have the rotational axis oriented perpendicular to the direction of the water flow.

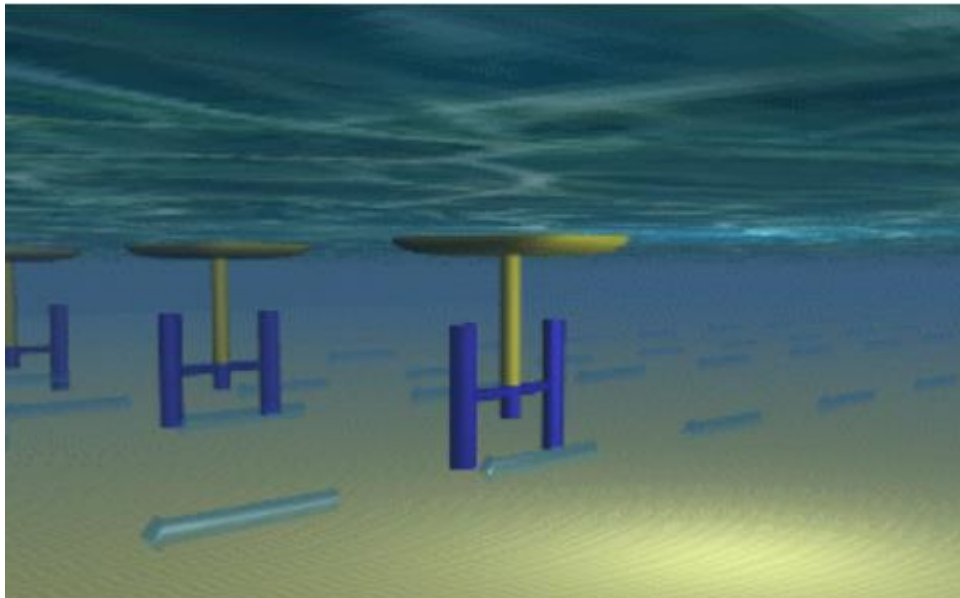


Figure 10: Vertical Axis Tidal Current Turbine [29]

**Verical axis TCTs** (see Figure 10) work analogously to vertical axis wind turbines. They can have two or three blades. The tidal stream causes the blades to rotate around the axis, generating power. They are usually more implemented for small and medium sites, such as in rivers [6]. The advantage of this kind of turbine for small sites is that it allows the turbine diameter to be greater than the depth of the site. This way, more area can be swept by the



rotor enabling a higher power generation [6]. Also, the vertical shaft allows the gearbox and generator to be above water, which allows an easier maintenance [30]. However, there are some problems associated with this configuration. They encounter high torque fluctuations with each revolution, and they lack of self-starting capabilities [26].

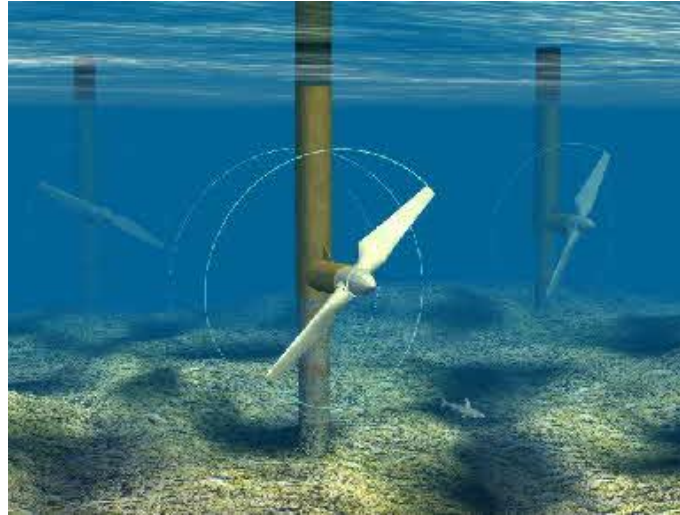


Figure 11: Horizontal Axis Two-Bladed Tidal Turbine [31]

**Horizontal axis TCT** rotate around a shaft that is parallel to the water surface. Most of TCT are nowadays designed with a horizontal shaft, since their technology is the most developed and mature [32]. They can also be two-, three- or multi-bladed. Multi-bladed turbines can generate a higher starting torque while reducing balancing problems originated in single-bladed devices. But the hydrodynamic losses increase with the number of blades, and that can be an inconvenience for multi-bladed devices [26]. An example of a horizontal two-bladed turbine is shown in Figure 11. Three-bladed TCT (see Figure 12) are the most common devices [33]. They are generally designed for 2 to 4 m/s stream velocities, while wind turbines are calculated to operate under 11 to 13 m/s. But since water is about 830 times denser than air [34], tidal turbines undergo a much higher thrust.

The power in the tide can be expressed as:

$$P = \frac{1}{2} * \rho * A * V^3 \quad (2.1)$$

Where:

- P is the power present in the water stream
- $\rho$  is the water density
- A is the rotor swept area
- V is the water speed



**Figure 12: Horizontal Axis Three-Bladed Tidal Turbine**

The extractable power is the fraction of this power that can be extracted from the tide by a tidal device. It is calculated by multiplying this power by a power coefficient. The power coefficient is defined as the actual extracted power over the total power available in the flow. The extractable power has a theoretical limit, so not all the kinetic energy present in the water stream can be converted. This is the Betz limit, and is equal to 59.3% [6]. This limit is expressed in the power coefficient, which will be then less than 0.593.

### **2.2.2 Tidal Turbine Blades**

Turbine blades are composed by airfoils with decreasing thickness from root to tip. This distribution aims to accommodate both structural and aerodynamic needs [35]. There is not much specific literature and studies about airfoils for tidal turbines [36]. However, knowledge on that field can be derived from wind turbine airfoils if some requirements are taken into account. The biggest difference between water and air as a working fluid is the risk of cavitation. This phenomenon is the formation of water vapour bubbles in a region where the pressure of the liquid falls below its vapour pressure [36].

Tidal stream devices are designed to last 20 to 25 years. Moreover, their location is an incentive to ensure that a low maintenance is needed [37]. These two reasons endorse the proper design of tidal turbine blades, in order for them to last as long as they are expected.

Tidal turbine blades have a smaller cross-section and suffer from higher loads than wind turbines. Therefore, they require a higher strength and stiffness. Resistance to corrosion and moisture, and fatigue degradation are also required. Hence, the structural laminates need to be very thick along the blade [33]. Internal reinforcements are made to ensure their stiffness, making them almost rigid [37] while wind turbine blades are mostly hollow.

Most adequate materials to use are glass and carbon reinforced composites. Specifically, carbon fibre laminates are advantageous to glass fibre laminates due to a higher strength in fatigue [33]. However, these composite laminates can generate problems in the manufacture phase [33]. Composite materials are only available in limited thicknesses, so the manufacture of a thick blade shell involves many plies to be laminated and thus many labour hours. Apart from that, the curved shape of the blades require strategic cutting of the plies to accommodate them in the mould. With the results of this thesis it is aimed to extract such restrictions and requirements towards the blade manufacturing process.

### 3 Evaluation of Tidal Energy

In this section of the thesis, an evaluation has been performed to compare tidal energy to other energy sources. To carry out an accurate comparison, quantitative indicators have been used. Thus, a numerical comparison will be possible. The first section of this chapter presents the selection of parameters to be evaluated. The next one shows the comparison between different values of these parameters for the above mentioned energy sources.

#### 3.1 Determination of Factors to Evaluate

In order to enable a simple and rigorous comparison, parameters should be measurable in a quantitative way. This way, a numerical value can be attributed to each energy source to be compared, permitting an easy and direct interpretation. Therefore a requirement for these indicators is the quantitative aspect.

The parameters to be evaluated have to represent aspects of importance regarding energy sources and the energy market. The concerns regarding the current energy share are mainly related to the **scarcity of resources** and **environmental impact** of each technology. About the depletion of some resources, the distinction between renewable and non-renewable energy resources has already been made in section 2.1.1. A resource can be whether renewable or not (depending if its resources are recovered in a measurable time or they are not) so no quantitative indicator is needed. The energy sources that are going to be evaluated in this chapter have already been classified according to this criterion in the State of the Art: coal, gas, oil and nuclear power are considered as non-renewable resources, while sun, wind, hydropower, biomass (and others such as geothermal) are renewable energy sources.

Apart from the lack of infinite resources of some energy fuels, it is also important to take into consideration the **environmental impact** they have when generating power. This is a global important issue, which is making requirements towards energy production also increase. Therefore, environmental impact will be one of the aspects to be assessed in this evaluation.

It is not enough for an energy source to be clean and environmentally-friendly to penetrate the energy market and become worldwide used. The decisive factor is the **cost of energy generation**. Therefore the second element to consider is the economic aspect. This is a crucial crucial point for an energy technology that wants to compete in the energy market.

On the whole, two different elements will be considered in the evaluation: the **economic aspect** and **the environmental aspect**. On the following sub-chapters, a specific indicator for each of the aspects will be selected and defined.

### 3.1.1 Economic Indicator

The best way to economically assess an energy technology is to calculate the overall cost of generating energy and electricity. That means taking into account all the costs that have been undertaken in order to produce energy. The most common indicator in the literature is the **Cost of Energy (COE) or Levelized Cost of Energy (LCOE)**. According to the Nuclear Energy Agency and International Energy agency (2005), the LCOE is the **ratio of total lifetime expenses versus total expected outputs** expressed in terms of the present value. In other words, it is the total cost of installing and operating a project expressed in \$ or € per kWh of electricity generated over its life [3,20,38]. More specifically, total costs refer to:

- Installing costs
- Financing costs
- Taxes
- Operation and Maintenance (O&M) costs
- Salvage costs
- Incentives
- Revenue requirements

This way, a life-cycle approach (LCA) is used, which means the whole life-cycle of the energy production is accounted for. As shown, it includes **all capital, operational, maintenance and disposal expenditures incurred over the lifetime** of the project, resulting in a unit cost per kWh [39]. LCOE can be calculated through different formulas, the most common of which is:

$$LCOE = \frac{TLCC}{\sum_{n=1}^N \frac{Q_n}{(1+d)^n}} \quad (3.1)$$

Where  $TLCC$  is the Total Life-Cycle Cost  
 $Q_n$  is the energy output or saved in year  $n$   
 $d$  is the discount rate  
 $N$  is the analyzed period

As a result, an economic indicator is obtained with the same units for every technology. Thus, it enables different technologies to be compared, even with different e.g. scales of operation or investments costs [38]. Furthermore, it is widely used as an indicator for cost-effectiveness of energy production technologies [4,40].

However, there is some criticism to this indicator. A downside of LCOE is that it can vary depending on different markets, government incentives and taxations [1]. Also, it does not take into account for specific market or

technology risks, such as uncertainty in the future fuel costs; nor other elements such as intermittency and the need for back-up power [8].

### 3.1.2 Environmental Indicator

The environmental impact of an energy technology can translate into many harmful effects. Some of them are specific for each technology (e.g. noise pollution in wind energy turbines). Others can be studied across any technology. Even though some energy technologies are claimed to be emission-free, all anthropogenic means of energy production generate pollutants when their entire life-cycle is accounted for [40]. These are mainly the emission of certain gases, which contribute to **global environmental problems such as air pollution and climate change**. They are generally known as greenhouse gases.

**Greenhouse gases (GHG)** are those gases in the atmosphere that absorb and re-emit heat. They are mainly water vapor, CO<sub>2</sub>, methane (CH<sub>4</sub>), dinitrogen monoxide (N<sub>2</sub>O) and ozone. Carbon dioxide is the most common GHG emitted by humans (by quantity released and total impact on the global warming) [41]. As a consequence, some reports only include said gas. But studies are more complete if they include all GHG and not just CO<sub>2</sub> [41]. Human contribution increases their quantities in the atmosphere, causing global warming and climate change [41]. Specifically, in the energy sector there are many activities associated with GHG emissions: electricity generation by itself but also transport, construction, etc. [20]. Some energy technologies, such as solar or even nuclear power, are deemed to be carbon-free since the production of electricity alone does not generate such emissions. But if their whole life-cycle is accounted for, instead of only the operation of the plant and energy production, they actually produce pollutants and GHG [20].

Thus, the GHG emissions of a specific energy technology are a good indicator to its environmental impact when a **LCA** is made. This means, **emissions will be accounted for every phase of the energy production**, e.g. construction of infrastructures, operation, maintenance, waste disposal. It will be used as a parameter in this research to assess the environmental impact of different energy technologies.

This parameter is defined as the **emissions of GHG per kWh of generated electricity** by each type of energy source. As mentioned, emissions resulting from the use of a particular energy technology will be quantified over all stages of the technology and its fuel life-cycle [42].

Table 1: GWP of Different GHG

| GHGd                                    | GWP          |
|---|--------------|
| Carbon Dioxide (CO <sub>2</sub> )       | 1            |
| Methane (CH <sub>4</sub> )              | 25           |
| Nitrous oxide (HFCs)                    | 298          |
| Perfluorocarbons (PFCs)                 | 124 – 14800  |
| Sulfur Hexafluoride (SF <sub>6</sub> )  | 7390 – 12200 |
| Nitrogen trifluoride (NF <sub>3</sub> ) | 17200        |

To quantify the emissions of different GHG in a common unit, the *carbon dioxide equivalent* is used. For the other gases, it represents the amount of actual CO<sub>2</sub> that would have the equivalent global warming impact. It is calculated by multiplying the amount of the GHG by its global warming potential (GWP) [41], and it can be expressed as “CO<sub>2</sub>e”, “CO<sub>2</sub>eq”, “CO<sub>2</sub>equivalent”, and “CDE”. The GWP of the most common GHG can be seen in Table 1. Carbon dioxide has the lowest GWP, even though it is the most abundant emitted gas.

### 3.1.3 Other Possible Indicators

Apart from the LCOE and GHG emissions (explained in sections 3.1.2 and 3.1.3), other indicators have been found in the literature. Their goal is also to compare a common magnitude among different energy sources. For example, the **efficiency** of the technology currently available for a specific energy source can be measured. However, this value by itself does not offer vital information about the energy sources to compare them. The repercussion of the efficiency for a specific technology will be taken into account when calculating the LCOE; but as a number alone it does not imply if it causes huge losses or not.

Also the **availability** of different energy sources [18,43–46] is a factor found in several studies. This aspect of energy sources is of special interest for fuels with resources constraint. However, there is no common way to measure or availability. It remains a factor to take into account but it will not be quantified by itself. Moreover, the effects of the availability of each energy source will be accounted for in their LCOE. This parameter considers the whole life-cycle of the energy production, and will therefore include the economic impact of a lower availability of a specific fuel or source (e.g. LCOE of coal takes into account the costs of exploring, mining and extraction, that are directly affected by the availability of the source and the site).

Finally, the concept of **energy security or security of supply** is also recurrent in the literature [18,19,47–50]. However, there is no consistent definition for it across the studies, since different aspects are covered in the literature. Source [47] reviews some approaches to measure energy security, such as supply/demand or diversity based indexes. Source [18] proposes to use four specific parameters to measure energy security: availability, accessibility, affordability and acceptability. Furthermore, numerous definitions have been used by researchers. Research made by [48] shows what parameters are more common among energy security definitions (e.g. availability and energy price) while showing many other factors that appear across the literature when measuring energy security (e.g. efficiency and governance). Moreover, it states that there is no widely accepted definition or quantification of this indicator.

### 3.2 Evaluation of Tidal Energy versus Conventional Sources

This section presents an evaluation of tidal energy in comparison to the other energy sources presented in the state of the art chapter. The comparison is based on the indicators selected in the previous section: **Levelized Cost of Energy (LCOE) and Greenhouse Gases (GHG) emission**.

To perform this evaluation, a deep search in the literature was conducted. As a result, a set of surveys and researches was collected. In each of them, one or more energy sources are studied regarding their LCOE or GHG emissions. Publications from before year 2000 were cut off the research in order to avoid too out-of-day technologies or estimations. In the following sections, the results will be analysed and contrasted with one another with two purposes: on the one hand, to understand the variability of data within each energy technology, since every study shows different values for the same indicator and energy source; on the other hand, to compare the values of each indicator for all the energy sources.

Through this assessment, a general overview of the primary energy sources will be given from two different perspectives: the economic angle and the ecologic one. In the discussion of results of section 3.3, these two aspects are brought together to evaluate what energy source is worth what.

#### 3.2.1 Economic Comparison (LCOE)

This section will present the results of the literature review about the economic indicator. In Figure 13 can be seen the range of values found for the LCOE of each energy source. All the costs have been presented in **cents of US dollar per kWh (¢/kWh)**. Most of the literature found was already in said currency; for the articles that used Euros or other currencies, the values have been converted to US dollars according to the exchange rate of the year of the publication.



**Renewable energy is highly context and location specific.** Therefore, resource availability and suitability for different markets differs considerably around the world [51] causing highly variable costs of energy.

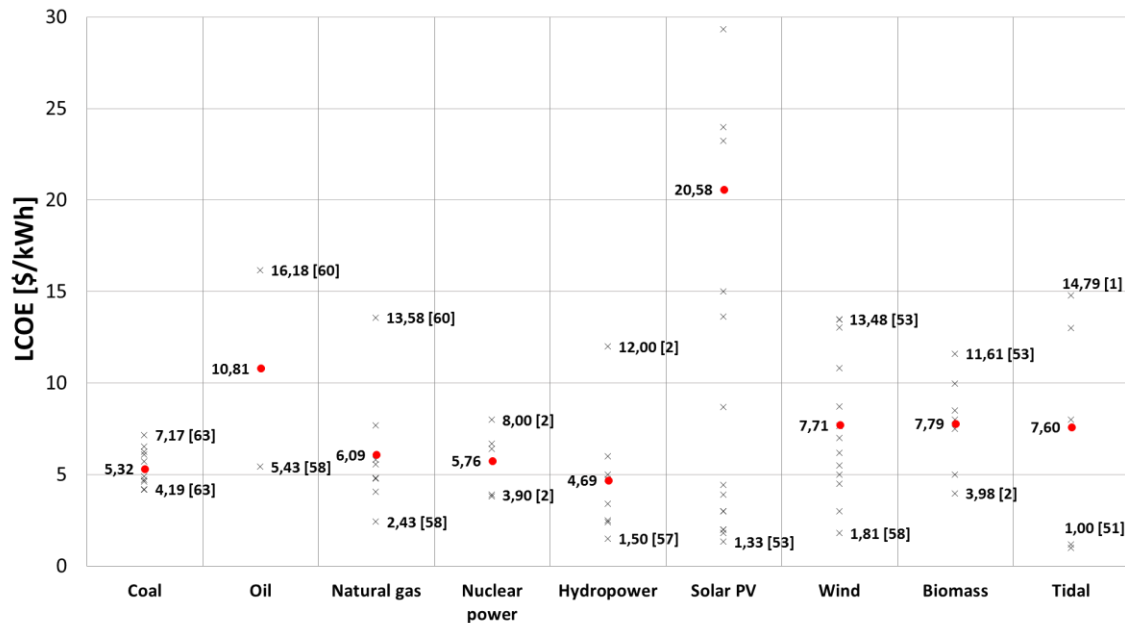


Figure 13: LCOE by Energy Source

Among both renewable and non-renewable energy sources, **solar PV is the most expensive energy technology**. The range of costs found in the literature is also the widest, as can be seen in Figure 13. According to [1,2,11,44,50–60], LCOE of solar PV ranges from 13.3 to 94.53 ¢/kWh. A life-cycle cost of 94.53 ¢/kWh is estimated by source [60] because it studies a relatively small solar PV system (2,7 kW). This value has not been represented in the graph in order to maintain a scale that allows the comparison between the other values for LCOE. The capital costs of solar PV systems, mainly driven by the manufacturing of the modules, account for more than 95% of its whole life-cycle costs. These capital costs are expected to be reduced for a larger solar PV system. The lowest cost is given by [53], which provides costs of solar PV generated electricity for several plants in China.

By contrast, **hydropower is the cheapest technology** currently available, with an **average cost of 4.69 ¢/kWh** [2,44,57,61,62]. A cost range of 6 to 12 ¢/kWh is the highest estimated LCOE for hydroelectricity, estimated by [2]. According to this source, hydropower has high capital investment costs. Also, the remote locations of potential sites result in high transmission costs. The lowest costs are the range from 1.5 to 2.4 ¢/kWh given by [57], a study that calculates the average costs of different energy sources in Lebanon.

It is followed by **coal**, with an **average cost of 5.32 ¢/kWh**. The values found in the literature (see Figure 13) range from 4.19 to 7.17 ¢/kWh. Both of these

values are estimated by [63], which compares different technology options for electricity generation from coal. The variety of technologies leads to a diversity of LCOE even for the same resource (coal). More literature has been found regarding coal [11,44,62,64,65] that estimate LCOE values within that range. They are focused on different energy sources (e.g. sources [11,65] consider solar energy, source [62] focuses on hydroelectricity and source [64], nuclear power) as well as on different locations (e.g. source [62] studies the energy options in Scotland while source [11] examines the Indian economy and energy production).

Another energy source with low LCOE is **nuclear power**, which has an **average cost of 5.76 ¢/kWh**. The results of the literature research for nuclear power were not as extensive as for other energy sources. The LCOE ranges from 3.9 to 8 ¢/kWh according to [2]. Other sources [63,64] estimate the cost of nuclear power within this range. Source [64] is focused on the advantages of nuclear power as an alternative to fossil fuels, and source [2] uses information from the International Atomic Energy Agency. Therefore, they are more likely to present a low LCOE for nuclear power.

**Natural gas has a slightly higher LCOE than coal**, with an **average cost of 6.09 ¢/kWh**. The highest LCOE is estimated by [60], which studies the life-cycle of different power generation technologies in Singapore. Hence, **nuclear power plants are competitive with coal- and natural gas-fired power plants**, whose average costs are 5.32 ¢/kWh and 6.09 ¢/kWh. In both cases, the range of values found is not very wide: 4.19 to 7.17 ¢/kWh for coal [11,44,62–65] and slightly broader for natural gas, 2.43 to 13.5 ¢/kWh [44,58,60,62–64]. Natural gas powered plants costs are very sensitive to the price of natural gas [64], and therefore the values obtained can differ depending on the time or location of the assessment.

**The main source of cost for nuclear generated electricity is the construction of power plants**, due to their high level of safety requirements. These new nuclear power plants cannot compete against natural gas technologies where gas infrastructures are already built up. But new nuclear power at this generating cost can be competitive with coal and gas especially when the fossil fuels have to be transported over long distances and these infrastructures are not yet in place [2].

The last fossil fuel, **oil**, is not commonly used for electricity generation, but more in the transportation sector. Hence, energy production from oil is not especially competitive with other fossil fuels. However, only two sources have been found that provide a value for its LCOE. On the one hand, energy generation with oil costs around 5.43 ¢/kWh according to [58], a value comparable to the other fossil fuel's prices. On the other hand, according to [60], energy generation in oil-fuelled power plants costs 16.18 ¢/kWh. This paper assesses life-cycles of

several energy sources present in Singapore, and states that oil-generated energy is highly dependent on oil price.

Among the other RET, the literature review showed that **tidal energy could achieve similar costs to wind energy**. According to [1,2,39,44,50,51,53,57,58,62,63,66–68], the **average cost of wind energy is 6.56 ¢/kWh**. The values found range from 1.81 up to 33.14 ¢/kWh. This relatively wide range is due to the fact that the literature about wind energy costs is more extensive than for other technologies. These publications cover a wide variety of countries, whose wind resource is different, as well as their discount rates. Also, two different technologies are accounted for: onshore and offshore wind turbines. In general, offshore wind turbines are more expensive, since their deployment is still small and their installation is more difficult (and therefore expensive) than onshore turbines [51]. Three of the highest values found: 19.48, 13.26 and 10.13 ¢/kWh, are taken from sources [39] and [62], which study specifically offshore wind turbines.

On the contrary, the lowest value for wind power is 1.81 ¢/kWh from source [58]. The research has been conducted in Egypt, which has some specific sites at the Gulf of Suez where annual wind speed average reaches 8.5 m/s. This might be the reason for the low estimation for the cost of energy.

With respect to **tidal energy**, the **average COE is almost the same as for wind energy: 7.6 ¢/kWh**, ranging from a very low cost such as 1 up to 14.79 ¢/kWh. Both wind and tidal energy technologies are **heavily dominated by the initial construction expenditures** [63]; mostly driven by the supporting structure and device installation. It has to be taken into account that not so many LCOE evaluations for specific plants can be found in the literature due to the early step of development of this technology. In addition, the evaluation is sometimes referred to a single turbine instead of a whole plant, which makes the costs look higher. But even with these considerations it looks like tidal energy could be competitive in the energy market if properly developed.

### 3.2.2 Environmental Comparison (GHG Emissions)

This section presents the results of a deep literature research that was conducted in order to collect data about the **GHG emissions of different energy sources**. Its results are depicted in Figure 14. In the graph can be seen the nine energy sources studied in this thesis. For each of them, the values for GHG emissions collected from different papers are shown in a column.

**Average emissions of coal-fired plants is 1003 g CO<sub>2</sub>eq/kWh**, and the collected values range from 1280 to 790 g CO<sub>2</sub>eq/kWh [44,46,49,69–75]. However, the highest value that has been found (1280 g CO<sub>2</sub>eq/kWh [69]) is far from the mean value and at a large distance from the next value found (1102 g CO<sub>2</sub>eq/kWh) so it is considered to be less representative. In all

cases, the vast majority of the gases, more than a 90%, are emitted during the burning of the fuel[70].

Regarding the GHG emissions found for **oil**, the collected data are more evenly spread along the range of values, from 1190 to 519 g CO<sub>2</sub>eq/kWh [10,46,49,69,70,73–75]. A reason for it can be that the number of studies found about oil-fired power plants is less than for coal or other energy sources (7 while for e.g. coal is 11). As electricity generation is not the main use of oil as fuel, the literature for it is not as extensive. The higher values equal the emissions of coal-generated energy, but the range reaches much lower emissions. According to these, the **average GHG emissions for oil-fired power plants are 810 g CO<sub>2</sub>eq/kWh**, while for coal are 1003. However a higher share correspond to the fuel combustion, up to a 95% [70].

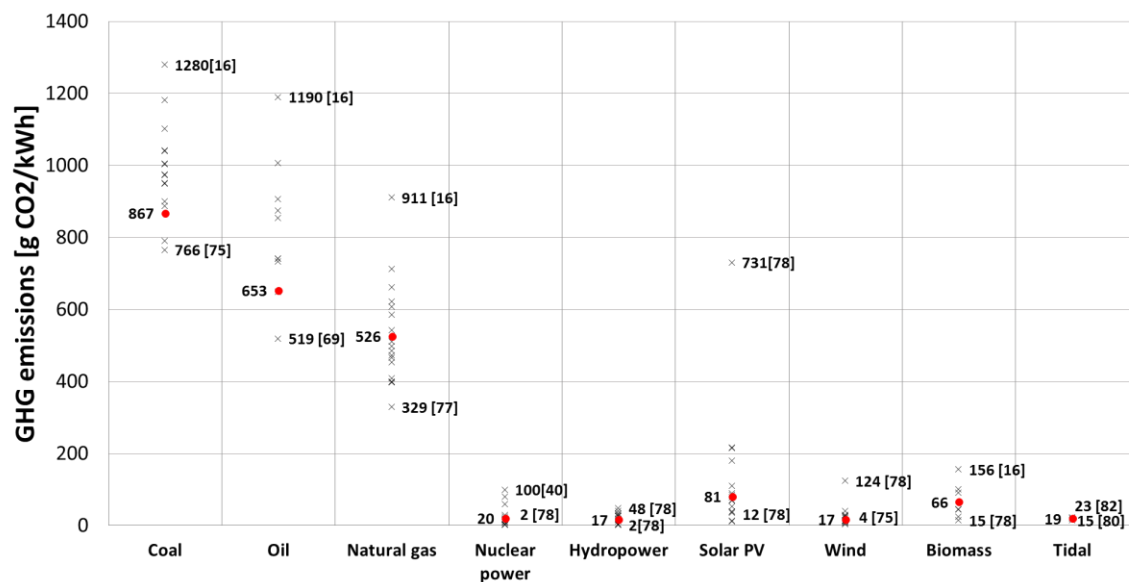


Figure 14: GHG Emissions by Energy Source

Life-cycle of **natural gas generates significantly less GHG emissions than oil and coal, 556 g CO<sub>2</sub>eq/kWh as average**, ranging from 398 to 712 g CO<sub>2</sub>eq/kWh [10,44,46,49,69,70,73,74,76,77]. Also, a lower share of these emissions is generated during the combustion of the fuel (less than 80%) and a higher part is emitted in the operation of the plant [70]. As well as for coal, a much higher value was found in one of the papers: 991 g CO<sub>2</sub>eq/kWh [69]. But it has been considered as isolated, since it almost doubles the average emissions for natural gas and is also distant from the next value (712 g CO<sub>2</sub>eq/kWh).

It should be pointed out that for the three fossil fuels here accounted (coal, oil and natural gas) the maximum value was found in the same article [69]. In this paper, the author provides a range of GHG emissions for some energy systems in order to compare them.

As for **nuclear power**, it can be seen in Figure 14 that emissions are considerably lower. The average of GHG emitted is 25 g CO<sub>2</sub>eq/kWh, ranging from 2 to 100 [40,49,69,70,72–75,75]. Compared to coal, life-cycle GHG emissions per unit of electricity from **nuclear power plants are at least one order of magnitude lower than those from fossil-fuelled electricity generation, and comparable to most renewables** [2]. More than 50% of the emissions are generated in the **process of enrichment of the fuel** [70]. The type of enrichment has a high influence on the total emissions, since gaseous centrifuge enrichment requires a lower amount of energy than gaseous diffusion, leading to less GHG emissions. Also the operation of the power plants contributes to the emission of GHG, even though this stage is attributed with different values depending on the methodology used to estimate them [40].

**Solar PV is the renewable energy system that has higher emissions**, ranging from 13 to 216 g CO<sub>2</sub>eq/kWh [40,44,49,69,70,73–75] and even up to 713 g CO<sub>2</sub>eq/kWh according to [78]. It emits 142 g CO<sub>2</sub>eq/kWh as average, while the rest of RET's average emissions are below 100 g CO<sub>2</sub>eq/kWh. **More than a 75% of these emissions are produced during the construction** of the PV modules [70]. Hence, PV modules are both cost- and energy-expensive.

Among the other RET (wind, hydro, biomass and tidal) **biomass** has the highest emissions, even though they are all relatively low. GHG average emissions of biomass energy production are 72 g CO<sub>2</sub>eq/kWh [49,69,73–75], followed by wind power (28 g CO<sub>2</sub>eq/kWh [44,49,69,70,72–75,79,80] and hydropower (21 g CO<sub>2</sub>eq/kWh [44,49,69,70,73–75,81]). **Emissions from wind and hydropower are comparable to nuclear power.**

Regarding **tidal power**, specific data for the life-cycle GHG emissions has been found. Source [82] suggests a value of 23 gCO<sub>2</sub>eq/kWh, which is the highest found. This value is an estimation based on the life-cycle study of this technology. In addition, it states that **environmental impacts related to tidal power are caused mainly by mooring, foundations and structural components**. A value of GHG emissions around 15 gCO<sub>2</sub>eq/kWh is provided by [80], that increase up to 20 gCO<sub>2</sub>eq/kWh when recycling is considered. This study is a life-cycle assessment of the Seagen marine turbine, the first commercial-scale grid-connected tidal energy installation located in the UK coast. This assessment also compares the emissions in the stage of the manufacture when using different materials in the construction. According to the study, **the materials and manufacturing stage emits up to 85% of the total GHG emissions**.

There is a huge gap between the emissions generated by fossil fuels (coal, oil, natural gas) and those from nuclear or renewable energy sources (hydropower, wind, solar PV, biomass, tidal). Fossil fuels generate at least 80% of their GHG emissions (especially CO<sub>2</sub>) in the combustion stage [70]. RET produce zero

emissions in the actual production of energy, but the construction of the necessary infrastructures generates more than 70% of the GHG emissions [70].

### 3.3 Discussion of Results and Outlook

This section of the thesis has presented the evaluation of two parameters measured for different energy sources. The aim of this evaluation was to make an assessment of tidal energy in comparison with other mature and developed energy technologies, as well as with other emerging renewable sources.

**Fossil fuels have been proved to be cheap in the energy generation, but also have very high levels of harmful emissions.** Nuclear power is also cheap, and has lower GHG emissions. could replace baseload fossil fuel electricity generation in many parts of the world if acceptable responses were found to concerns over reactor safety, radioactive waste transport, waste disposal and proliferation [2]. But so far they remain unsolved issues and nuclear power is not likely to recover from the downturn caused by the nuclear accidents happened in the past years (e.g. Three Mile Island in 1979, Chernobyl in 1986 or Fukushima in 2011).

Overall, **most of the RET still need major technology developments to be considered as real candidates to compete in the energy market** with traditional fossil fuels. Especially solar PV has high LCOE and high GHG emissions, which could be due to non-fully developed technology and manufacturing methods, which make the construction stage proportionally very expensive.

Regarding tidal energy, it proved having the **potential to become meaningful in the future if properly developed**. According to the results found, it is comparable to wind energy in terms of cost of electricity production, even though only individual projects have been accounted. In conclusion, it would make sense to invest in developing this type of technology in order to achieve economies of scale and be able to compete with the current resources that dominate the market.

## 4 Design of a Tidal Turbine Blade

This chapter corresponds to the second part to the thesis: the development of a blade for a tidal turbine. As stated in the research design, the first step will be to define the specific goals that want to be achieved through this design. Once the target is clear, the next sub-section exposes how the software choice was made, which leads to the final approach followed to the blade design. Finally, the actual blade design will be described and its output presented.

### 4.1 Goal

In this section, the target of the blade design will be defined. As has already been mentioned throughout the thesis, the ultimate goal of designing a blade of a tidal turbine is to infer from it the possible requirements for the manufacturing process in a posterior study. Precise data about the shape of the blade is needed. Therefore, the focus of the design is to deliver the **geometry specifications of the blade**. The detailed geometry encloses the external shape and internal structure.

The external shape of a blade is defined by the **foil section**, and the **chord and twist distribution** for the blade span. The chord is the distance between the leading edge and the trailing edge (see Figure 15), and the twist is the angle of deviation between the chord line and the rotor plane. Wind and tidal turbine blades are twisted to maintain the optimal angle of attack (AoA) of the fluid along the blade. To define the blade shape, the chord and twist for every section of the blade are needed. These combined with the foil section will define the external shape of the blade. It is what in Figure 15 is shown as *external surface*, also known as shell. The **thickness of the shell** needs also to be specified, since it will determine the number of material plies.

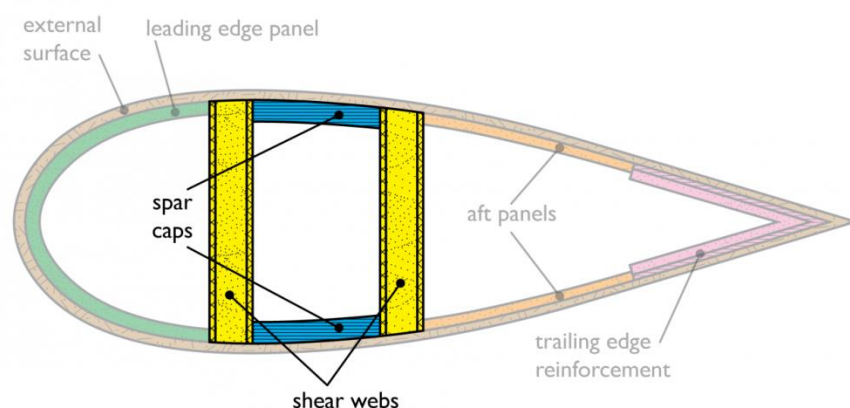


Figure 15: Schematic Internal Structure of a Blade [83]

A hollow shell is not enough to resist all the loads suffered by the blade [84]. To strengthen the blades, one or more shear webs are generally added inside the blade (see Figure 15). They are reinforcements of material perpendicular to the

chord. The **position and thickness of the shear web** is also needed as part of the geometry of the blade.

To assemble all the characteristics of the blade, the simplest way is to visually represent it. Therefore, a 3D file to show the final design is wanted.

Among the different designs presented in the State of the Art chapter, a **three-bladed horizontal axis tidal turbine** has been chosen for this design.

## 4.2 Software Choice

This section will present the software chosen to design the blade, and the procedure that will be followed to performing it. **What are the needed characteristics or features the software should have in order to meet the objectives set?** It has been stated that the primary outcome has to be the detailed geometry of the blade, and this should be allowed by the used software. A detailed description of the geometry is therefore mandatory.

Regarding the blade design and optimization, there are some programs specialized in wind turbine blades. For this project, they are suitable if some points are addressed. First, the program has to allow using specific airfoils suitable for tidal turbines. Airfoils with this purpose are generally called **hydrofoils**, but are conceptually the same. But even though there are some programs that already work with the most known and proven airfoils for wind turbines, there is not any with hydrofoils. Therefore, even if a wind turbine-specific program is used, it has to include or allow the importation of other foils. In addition, it is important that the software allows **designing, modifying and visualizing the internal structure** described in section 4.1 and not only the external aerodynamic shape. This should deliver a detailed geometry of the blade. Moreover, the structural optimization requires the concerning material properties to be defined by the user.

The actual software that has been considered are mainly *QBlade* and *HARP\_Opt*. Some other has been studied but discarded, such as *HELICIEL* (a software to calculate and design wind and tidal turbines that includes some foil data [85]), *MSC Software* [86] and *Tidal Bladed* [87]. The main reason was their price, which does not meet the purposes of this thesis. Instead, both *QBlade* and *HARP\_Opt* are open-source software of free access.

**HARP\_Opt is a Horizontal Axis Rotor Performance Optimization** software with *MATLAB*'s algorithms and Blade-Element Momentum (BEM) theory code to design axial-flow wind and water turbine rotors. Its interface can be seen in Figure 16. Its primary objective is to maximize the Annual Energy Production (AEP). It also offers the possibility to perform a structural optimization, so it becomes a multi-objective optimization code. The objective of the structural optimization is to minimize the blade mass while satisfying the allowable strain. Furthermore, it provides a specific constraint to avoid cavitation if a hydrokinetic turbine is being modelled.



## HARP\_Opt v2.00.00

**Turbine Configuration**

☐ Rotor Speed Control  
☒ Fixed Speed  
☐ Variable Speed

☐ Blade Pitch Control  
☒ Fixed Pitch (Stall Regulated)  
☐ Variable Pitch (Pitch to Feather)  
☐ Variable Pitch (Pitch to Stall)

NumBlade: 3 Number of blades  
 NumSeg: 30 Number of blade segments  
 Prated: 200 Rated rotor power (kW)  
 RotorDia: 10 Rotor diameter (m)  
 HubDia: 1.5 Hub diameter (m)  
 HubHt: 10 Hub distance from bottom surface (m)  
 PreCone: 0 Pre-cone angle (deg)  
 ShaftTilt: 0 Shaft tilt angle, positive up (deg)  
 OmgMin: 5 Minimum allowable rotor speed (rpm)  
 OmgMax: 20 Maximum allowable rotor speed (rpm)  
 OmgMax: 10.5 Maximum possible blade tip speed (m/s)

☒ Hydrokinetic Turbine (check for cavitation)  
 Pvapor: 2500 Water vapor pressure (Pa) absolute  
 Patm: 101325 Air atmospheric pressure (Pa) absolute  
 WatDepth: 22 Distance from water surface to bottom (m)  
 CavSF: 1.0 Cavitation safety factor  $\geq 1$

**Fluid Properties**

Rho: 1025 Fluid density (kg/m<sup>3</sup>)  
 KinVisc: 1.06e-6 Kinematic fluid viscosity (m<sup>2</sup>/s)  
 SpdSt: 0.2 Minimum flow speed (m/s)  
 SpdEnd: 3.0 Maximum flow speed (m/s)  
 SpdDel: 0.1 Flow speed increment (m/s)

**Energy Estimates**

AEP: 247,000 Estimated AEP (kWh/yr)  
 CF: 14.1 Estimated Capacity Factor (%)

Axis Limits: min max  
 RotorDia: 8 12 (m)  
 Prated: 100 250 (kW) Plot Contours

**WT\_Perf Algorithm Configuration**

TipLoss: ☒ True ☐ False Use the Prandtl tip-loss model?  
 HubLoss: ☒ True ☐ False Use the Prandtl hub-loss model?  
 Swirl: ☒ True ☐ False Include rotational wake effects?  
 AdvBrake: ☒ True ☐ False Use advanced brake-state model?  
 IndProp: ☒ True ☐ False Use PROP-PC instead of PROPX induction algorithm?  
 AIDrag: ☒ True ☐ False Use the drag term in the axial induction calculation?  
 TIDrag: ☒ True ☐ False Use the drag term in the tangential induction calculation?  
 MaxIter: 1000 Max number of iterations for induction factors  
 ATol: 1.0e-6 Error tolerance for induction iteration

**Stall Delay Models**

☐ No stall delay (just use 2D lift and drag coefficients)  
☐ Lift and drag coefficients corrected via SeligDu method  
☒ Lift corrected via SeligDu, drag corrected via Eggers method

**Optimization Objectives**

☒ Optimize efficiency  
☒ Optimize annual energy production (AEP)

**Flow Distribution**

☐ Not defined (AEP will not be calculated)  
☐ Rayleigh Distribution  
 U: 6.03 Long-term mean flow speed (m/s)  
☐ Weibull Distribution  
 k: 1.91 Shape factor  
 c: 6.8 Scale factor  
 U: 6.03 Long-term mean flow speed (m/s)  
☒ User-Defined Distribution  
 Select File Marrowstone\_Island\_C5.dat

☒ Perform Structural Optimization (Multi-Objective)

E: 27.6 Modulus of elasticity of bulk material (GPa)  
 MatDensity: 1800 Density of bulk material (kg/m<sup>3</sup>)  
 MaxStrain: 3000 Allowable strain (micro-strain)  
 SF: 1.2 Safety factor multiplied to bending moments  
 STmin: 1 Minimum shell thickness (mm)  
 STdel: 0.2 Shell thickness increment (mm)  
 DecST: ☒ True ☐ False Monotonically decreasing shell thickness?

**Blade Geometry Configuration**

ElmSpc: ☐ Equal ☒ Cosine Blade element radial spacing

**Pre-Twist and Chord Distributions**

| CP radius: | 0.75 | 1.074 | 1.995 | 3.374 | 5    | (m)                          |
|------------|------|-------|-------|-------|------|------------------------------|
| TwistLB:   | 0    | -10   | -10   | -10   | -10  | Twist lower and upper bounds |
| TwistUB:   | 40   | 40    | 40    | 40    | 40   |                              |
| ChordLB:   | 1.3  | 0.05  | 0.05  | 0.05  | 0.05 | Chord lower and upper bounds |
| ChordUB:   | 1.3  | 1.3   | 1.3   | 1.3   | 1.3  |                              |

☒ Model blade with circular root chord  
 RtChordMin: 0.8 Minimum allowable root chord (m), or leave value blank  
 RtChordMax: 1.5 Maximum allowable root chord (m), or leave value blank  
 RtTranSt: 0.15 Start of root transition region (r/R)  
 RtTranEnd: 0.25 Maximum (r/R) location of max. chord (RtChordMax)

**Airfoil/Hydrofoil Distribution**

☒ Piecewise Linear ☐ Piecewise Constant

FoilFam: FFA Name of airfoil/hydrofoil family, i.e. "NACA"  
 ThickVals: 30 24 21 Available foil % thickness values 100%(t/c)  
 (r/R) LB: 0.15 0.25 0.35 Foil lower bounds (r/R), use NaN's or blank  
 (r/R) UB: 0.15 0.31 Foil upper bounds (r/R), use NaN's or blank

**Genetic Algorithm Configuration**

☐ Seed initial population from "Initial\_Population.xls"  
 PopSize: 100 Number of individuals per generation  
 EliteCt: 1 Number of elite individuals per generation  
 ParetoFrc: 0.2 Fraction of PopSize to remain on Pareto front (approximate)  
 CrossFrc: 0.25 Fraction of individuals created by crossover  
 NumGen: 150 Max number of generations for GA iterations  
 GATol: 1.0e-6 Error tolerance for the GA fitness value

☐ Record Failed Cases  
 Filename: 200kW\_HydroTurbine Output filename  
Begin Optimization Save Settings Load Settings

Figure 16: HARP\_Opt Interface

The optimization performed by HARP\_Opt returns the parameter of the blade optimal shape (chord, twist, airfoil distributions). The main drawback of HARP\_Opt is that for the structural optimization, the blade is modelled only as a thin shell of bulk material, as shown in

Figure 17. No internal structure such as shear webs is taken into account.

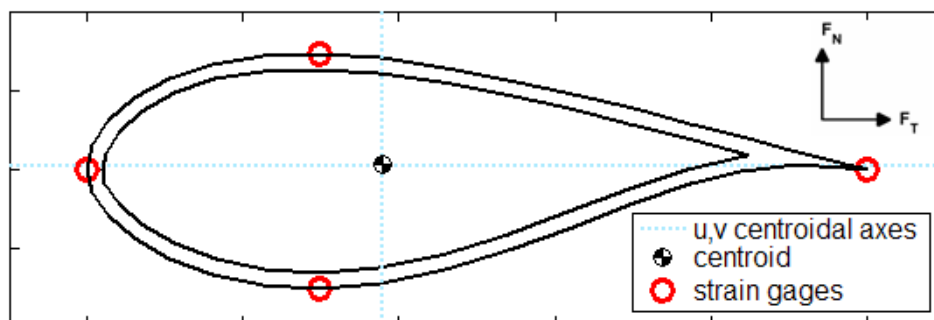


Figure 17: Representation of a Blade in HARP\_Opt

**QBlade** is a software for the **design and optimization of wind turbines**. It has three main modules: blade design and optimization; rotor simulation; and turbine definition and simulation. Unlike *HARP\_Opt*, the blade is designed by the user and the software calculates the corresponding AEP. Therefore, the

blade can be fully designed by the user, including the internal structure and its material properties (defined through the elastic modulus and the density). This blade geometry can also be exported as a *.stl* file.

**Table 2: Characteristic checklist for HARP\_Opt and QBlade**

| Characteristic        | HARP_Opt | QBlade              |
|-----------------------|----------|---------------------|
| Hydrofoil importation | Yes      | Yes                 |
| Internal structure    | No       | Yes                 |
| 3D file exportation   | No       | Yes ( <i>.stl</i> ) |
| Material definition   | Yes      | Yes                 |

All in all, both of them have some essential features as well as some deficiencies. On the one hand, *HARP\_Opt* generates the optimal blade shape for given set of specifications (see Figure 16), while taking into account the cavitation, but does not design the internal structure nor provides a 3D view of the blade. On the other hand, the interface of *QBlade* includes the 3D view of the blade geometry and allows the design of the internal structures. However, it does not provide with specifications for hydrokinetic turbines. Also, the whole blade shaping is up to the user, so there is no way of directly knowing if the designed blade is the optimal one for the given conditions. After a first approach with each of these programs, a combined approach is decided. Both programs will be used to achieve the best blade design possible.

### 4.3 Final Approach

As a starting point, specific input is given. The turbine is theoretically designed to be located in the coastal region of Singapore, in a site with an average flow speed of 3 m/s. Regarding the dimensions, the desired diameter is around 4 m; and regarding the material used, Carbon Fibre Reinforced Polymer (CFRP) will be uniformly used for all the structural parts of the blade.

First of all, an optimization has been run with *HARP\_Opt*. It requires defining the conditions under which the turbine will be working, as well as the setup for the turbine.

The first module is the **turbine configuration**; it describes how the turbine is arranged. In this module have to be introduced the turbine specifics, such as the number of blades, their length, the turbine height and the maximum allowable rotor speed (see Figure 18). The option for a hydrokinetic turbine can here be selected.

| Turbine Configuration  |        |  |
|--|--------|--|
| Rotor Speed Control  |        | Blade Pitch Control  |
| <input type="radio"/> Fixed Speed<br><input checked="" type="radio"/> Variable Speed |        | <input type="radio"/> Fixed Pitch (Stall Regulated)<br><input checked="" type="radio"/> Variable Pitch (Pitch to Feather)<br><input type="radio"/> Variable Pitch (Pitch to Stall) |
| NumBlade:  | 3      | Number of blades   |
| NumSeg:  | 30     | Number of blade segments   |
| Prated:  | 70     | Rated rotor power (kW)   |
| RotorDia:  | 4      | Rotor diameter (m)   |
| HubDia:  | 0.4    | Hub diameter (m)   |
| HubHt:   | 8      | Hub distance from bottom surface (m)   |
| PreCone:   | 0      | Pre-cone angle (deg)   |
| ShaftTilt:   | 0      | Shaft tilt angle, positive up (deg)  |
| OmgMin:  | 2      | Minimum allowable rotor speed (rpm)  |
| OmgMax:  | 40     | Maximum allowable rotor speed (rpm)  |
|  | 8.4    | Maximum possible blade tip speed (m/s)   |
| <input checked="" type="checkbox"/> Hydrokinetic Turbine (check for cavitation)      |        |  |
| Pvapor:  | 2500   | Water vapor pressure (Pa) absolute   |
| Patm:  | 101325 | Air atmospheric pressure (Pa) absolute   |
| WatDepth:  | 30     | Distance from water surface to bottom (m)  |
| CavSF:   | 1.0    | Cavitation safety factor $\geq 1$  |

Figure 18: Turbine Configuration Module of *HARP\_Opt*

Some assumptions have been made about the turbine configuration. The rated power has been calculated by equation (2.1) presented in section 2.2.1. A power coefficient of 0.4 has been used, as suggested by source [1] for tidal turbines. Based on the design developed by [32], the hub has been taken as a 10% of the rotor diameter. Regarding to the rotor speed, source [6] suggests that the optimal rotational speed for a three-bladed horizontal axis tidal turbine is around 35 rpm. Hence a maximum of 40 rpm has been accounted for. Finally, a water depth of 30 m has been taken from [88], a study that reviews the water depths in the Singapore Strait.

The next module is the **fluid properties** (see Figure 19): in this module, the properties of the fluid in which the turbine will be operating have to be defined. Properties of air are set by default. For designing a tidal turbine, properties of seawater have to be set. An average value for seawater density has been taken from source [89]. For the minimum and maximum flow speed, estimations were made around the average flow speed. Minimum is taken 0.25 m/s for being the closest to zero. Flow speed of 10 m/s has been set as an extreme condition, since the flow speed for the turbine is 3 m/s. Therefore, a flow speed of 10 m/s is highly unlikely, but frequent maintenance and repairing of the blade is to be avoided, so the blade is designed to the worst case scenario.

| Fluid Properties |         |   |
|------------------|---------|---|
| Rho:             | 1027    | Fluid density (kg/m <sup>3</sup> )            |
| KinVisc:         | 1.16e-6 | Kinematic fluid viscosity (m <sup>2</sup> /s) |
| SpdSt:           | 0.25    | Minimum flow speed (m/s)                      |
| SpdEnd:          | 10      | Maximum flow speed (m/s)                      |
| SpdDel:          | 0.25    | Flow speed increment (m/s)                    |

Figure 19: Fluid Properties Module of *HARP\_Opt*

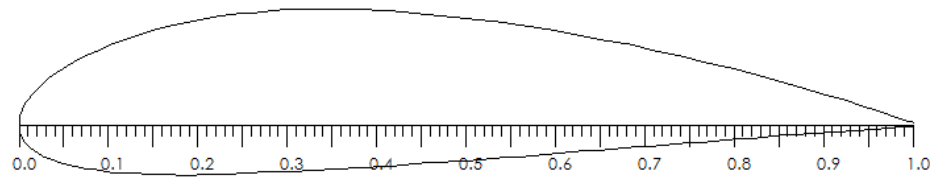
In the **optimization objectives** box, the goal of the optimization has to be set (see Figure 20). The main objective is to maximize the AEP of the turbine. The user has to select the flow distribution. In this case, a Rayleigh distribution has been chosen with a mean flow speed of 3 m/s. Apart from maximizing the AEP, this box offers to perform a structural optimization as well. When chosen, the user has to introduce the properties of the material that will model the blade (elastic module and density).

| Optimization Objectives  |   |   |
|--|---|---|
| <input type="radio"/> Optimize efficiency<br><input checked="" type="radio"/> Optimize annual energy production (AEP)    |   |   |
| Flow Distribution  |   |   |
| <input type="radio"/> Not defined (AEP will not be calculated)<br><input checked="" type="radio"/> Rayleigh Distribution |   |   |
| U:   | 3   | Long-term mean flow speed (m/s)               |
| <input type="radio"/> Weibull Distribution   |   |   |
| k:   | 1.91  | Shape factor                                  |
| c:   | 6.8   | Scale factor                                  |
|  | 6.03  | Long-term mean flow speed (m/s)               |
| <input type="radio"/> User-Defined Distribution  |   |   |
|  | Select File   | no file selected                              |
| <input checked="" type="checkbox"/> Perform Structural Optimization (Multi-Objective)                                    |   |   |
| E:   | 85  | Modulus of elasticity of bulk material (GPa)  |
| MatDensity:  | 1600  | Density of bulk material (kg/m <sup>3</sup> ) |
| MaxStrain:   | 3000  | Allowable strain (micro-strain)               |
| SF:  | 1.2   | Safety factor multiplied to bending moments   |
| STmin:   | 1   | Minimum shell thickness (mm)                  |
| STdel:   | 0.2   | Shell thickness increment (mm)                |
| DecST:   | <input checked="" type="radio"/> True <input type="radio"/> False Monotonically decreasing shell thickness? |   |

Figure 20: Optimization Objectives Module of *HARP\_Opt*

In the **blade geometry configuration** the user can specify some restrictions for the blade geometry (see Figure 22). For example, an option can be selected to design the root as circular. Regarding the airfoil, the desired airfoil or airfoils with which the user wants the blade to be designed can be specified. In this case, the NACA4418 airfoil has been used. According to the goal of this work, a generic and common hydrofoil was chosen among others considered (other airfoils in the NACA family, Riso-A family of hydrofoils). The NACA44XX family has been designed as a family of hydrofoils to be used in hydrokinetic

turbines [36,90] due to their higher thickness, meant to support the greater forces of water in comparison to wind.



**Figure 21: Profile of the NACA4418 foil**

Finally, in the genetic algorithm configuration the optimization details are set. As seen in Figure 23, the number of generations, the individuals per generation and other specific values for the genetic algorithm can be chosen. These were restricted by the reach of the software. With a high number of generations or individuals per generation, the software would not properly run and provide with results. Therefore, an optimization with a maximum of 45 generation was achieved with satisfying results.

**Blade Geometry Configuration**

ElmSpc: ☒ Equal ☐ Cosine Blade element radial spacing

Pre-Twist and Chord Distributions

| CP radius: | 0.5 | 0.6142 | 0.9393 | 1.426 | 2    | (m)                          |
|------------|-----|--------|--------|-------|------|------------------------------|
| TwistLB:   | -10 | -10    | -10    | -10   | -10  | Twist lower and upper bounds |
| TwistUB:   | 40  | 40     | 40     | 40    | 40   |                              |
| ChordLB:   | 0.5 | 0.1    | 0.1    | 0.1   | 0.1  | Chord lower and upper bounds |
| ChordUB:   | 1.5 | 1.5    | 1      | 1     | 0.25 |                              |

☒ Model blade with circular root chord

RtChordMin: 0.2 Minimum allowable root chord (m), or leave value blank

RtChordMax: Maximum allowable root chord (m) or leave value blank

RtTranSt: 0.2 Start of root transition region (r/R)

RtTranEnd: 0.25 Maximum (r/R) location of max. chord (RtChordMax)

Airfoil/Hydrofoil Distribution

☒ Piecewise Linear ☐ Piecewise Constant

FoilFam: NACA Name of air foil/hydrofoil family, i.e. "NACA"

ThickVals: 18 Available foil % thickness values 100\*(t/c)

(r/R) LB: Foil lower bounds (r/R), use NaN's or blank

(r/R) UB: Foil upper bounds (r/R), use NaN's or blank

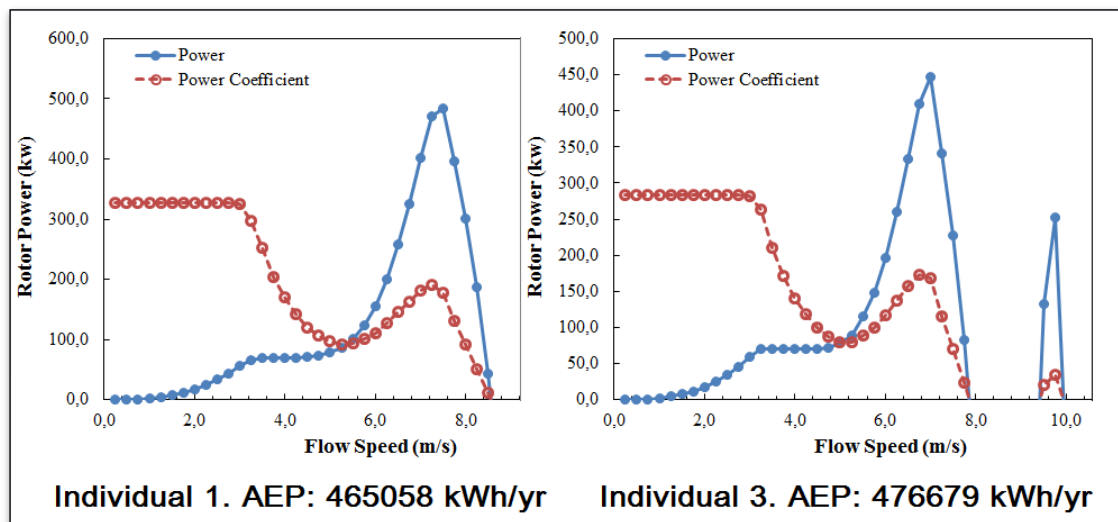
**Figure 22: Blade Geometry Configuration Module of *HARP\_Opt***

| Genetic Algorithm Configuration  |        |   |
|--|--------|---|
| <input type="checkbox"/> Seed initial population from "Initial_Population.xls" |        |   |
| PopSize:   | 50     | Number of individuals per generation                        |
| EliteCt:   | 1      | Number of elite individuals per generation                  |
| ParetoFrc:   | 0.2    | Fraction of PopSize to remain on Pareto front (approximate) |
| CrossFrc:  | 0.25   | Fraction of individuals created by crossover                |
| NumGen:  | 45     | Max number of generations for GA iterations                 |
| GATol:   | 1.0e-6 | Error tolerance for the GA fitness value                    |

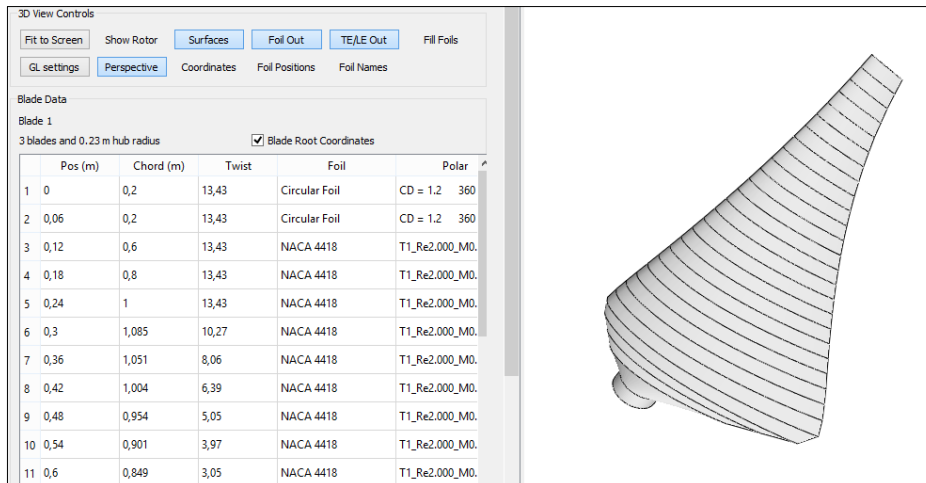
Figure 23: Genetic Algorithm Configuration of *HARP\_Opt*

The optimization in *HARP\_Opt* returned four optimal blade shapes. For each of them, the chord, twist and thickness distribution is given. Also an estimation of the AEP and the power output for each flow speed within the range specified is calculated, as well as other variables such as strain and stress suffered by each section.

Among the four optimal individuals, the two individuals that produced the highest AEP were initially chosen (see Figure 24). Between these two possible blades, the *Individual 1* was finally chosen since the power output is slightly higher for most of the flow speeds studied, and also the increase of power output for greater speeds is more stable. The selected individual weights 6.67 kg.

Figure 24: Power vs Flow Speed for two Individuals Generated by *HARP\_Opt*

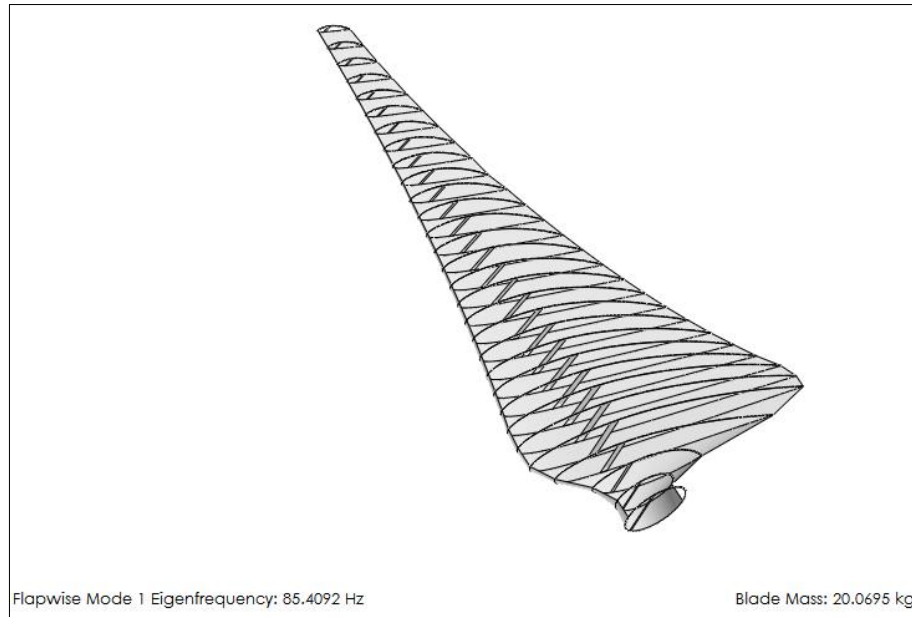
Once the individual is selected, the blade has been designed in *QBlade*. The chord and twist distribution can be directly input in the program, which then models the blade. Even though a circular root was selected in *HARP\_Opt*, some inconsistencies are found when modelling the blade in *QBlade*. It reports a solidity higher than 1 in the root area. Solidity is the ratio of the blade area to the area swept by the rotor [84]. Since solidity higher than 1 is not possible,



**Figure 25: Blade Design in QBlade**

some modifications were made in *QBlade* to design a feasible tidal turbine blade. The interface of the rotor blade design module of *QBlade* can be seen in Figure 25: Blade Design in QBlade: on the left side, the chord and twist distributions are introduced, while the right side shows a 3D figure of the modelled blade.

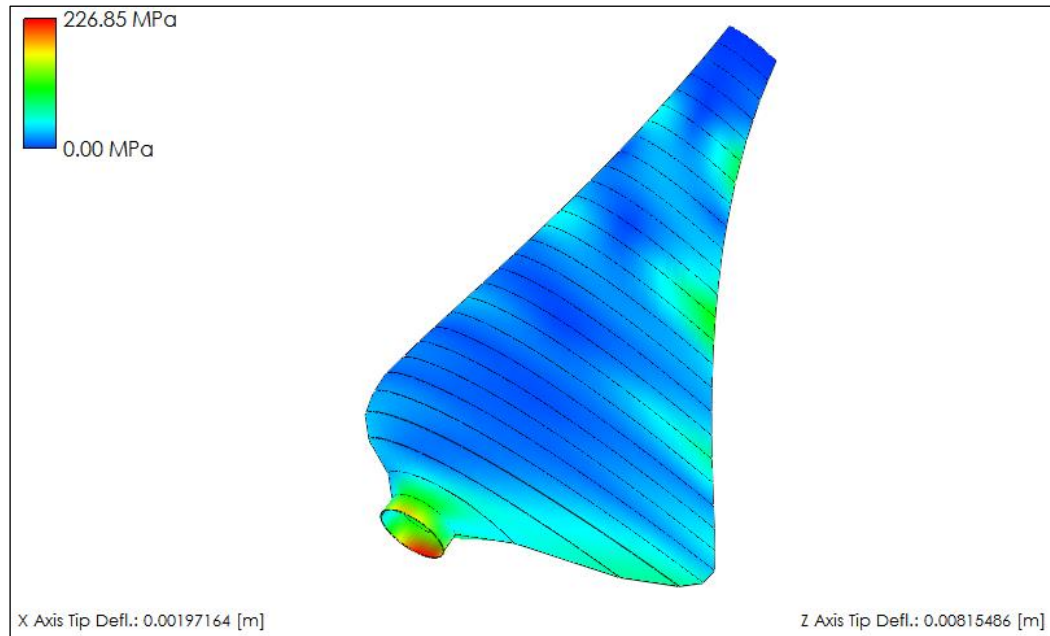
Apart from modelling the external shape of the blade, the internal structure can also be designed in another module of *QBlade*. This will add up some weight to the blade. A shear web has been added to the structure to reinforce the blade (see Figure 26). To resist the bending moments the cross-section needs to be strengthened with very strong material [33]. However, after some simulations the thickness of the shear web has been reduced around a 60% from the initial design to the final thickness. This way, the total mass of the blade is heavily reduced while the blade can still support the loads with a large safety factor.



**Figure 26: Internal Structure of the Blade**

After defining the internal structure and material properties according to those used in HARP\_Opt, theoretical loads have been applied to the blade in order to simulate its behaviour. First, the loads corresponding to a flow speed of 3 m/s has been applied, since it is the flow speed for which the blade is designed (see Figure 27). The deflection of the blade is negligible. As shows Figure 27, tip deflection in the X axis is less than 2 mm, while in the Z axis is a bit higher, around 8 mm. The maximum equivalent stress is suffered in the root ( $2.5\text{E}+08$  Pa) and is anyway lower than the considered elastic module (E) ( $8.5\text{E}10\text{Pa}$ ). However, the root should be designed separate from the rest of the blade, since it involves the connections to the hub.





**Figure 27: Blade Loading for Flow Speed of 3 m/s**

Then, a higher flow speed of 5 m/s has been applied to simulate more severe conditions. Again, the blade resists the loads with a large safety factor.

The result of this design is a generic blade for a tidal turbine developed with a foil from the NACA family. These foils are widely used for research and for wind turbines, and the foil here used has been specifically developed for hydrokinetic purposes. Hence from this blade it is expected to infer generic requirements or constraints that a blade of this characteristics could represent regarding its manufacturing method.

## 5 Conclusions and Summary

Energy consumption is constantly increasing, and it has been proved that fossil fuels, which nowadays are the primary energy source, are not a solution for energy supply in the long term. This creates the need to introduce new energy technologies to the energy mix. In addition, the dependence on fossil fuels has major environmental impacts. Some renewable sources are already being exploited, such as hydropower. But most of them still need major technology developments to be considered as candidates to compete in the energy market with traditional fossil fuels.

Among these developing technologies is tidal energy. This technology is still in its infancy, but it has high unexploited potential. In addition, it has a great advantage over other RET: **predictability**. Thus, it seems that tidal energy is a good alternative source of energy, but yet to be developed. To evaluate whether the development of this kind of technology is worth the effort, an evaluation of tidal energy in comparison with other energy sources has been made.

To perform the evaluation, two specific indicators have been used: Levelized Cost of Energy (LCOE) and Greenhouse-Gases (GHG) emissions. On the one hand, the economic parameter will measure if **tidal energy can potentially compete with deployed energy sources**, and if it looks more advantageous than other emerging renewable sources. On the other hand, a **whole life-cycle assessment of the emissions of certain gases** will help to evaluate the real environmental impact of generating energy through a specific technology.

After a literature search, several values for the LCOE of the selected energy sources have been gathered. Results are shown in section 3.2.1. Cost of energy is highly dependent on the location and type of technology used, which has led to variability in the results.

LCOE of fossil fuels is similar and very cheap, especially natural gas and coal. This is the result of many years of technology development and optimization, and the fact that the fuel harvesting is not expensive. This makes it **difficult for new energy technologies to penetrate the market**, since they have to compete for very low costs of generation.

According to these findings, nuclear power can be competitive in price with natural gas and coal. The main capital cost for nuclear power is the construction of new plants, since they have many safety requirements, while fossil fuels have already built up infrastructure. However, **it is debatable whether nuclear power should be endorsed and fostered as the energy alternative to fossil fuels**. There is existing scepticism regarding nuclear power plants concerning their environmental impact and safety risks, as well as concerning recent nuclear accidents such as Fukushima.

Regarding the renewable sources, **electricity produced by renewable technologies is typically more expensive than conventional forms of generation.** Most expensive energy technology according to these results is Solar PV. This is likely to be due to the high manufacturing costs, which should be downsized through economies of scale. In contrast, hydropower is the cheapest energy source, even cheaper than fossil fuels. This can be due to the fact that hydropower is one of the most exploited renewable sources, and even though the construction of infrastructure constitutes a high fraction of the capital costs, there are already many built up.

Finally, wind and tidal energy have similar LCOE, which is around 1 ¢/kWh higher than for fossil fuels. The LCOE for tidal energy is taken from the currently working projects, which are small or prototype turbines. This is very promising, **since the cost of generation could reach very low values with technologic developments and economies of scale.** Current costs are driven by the initial construction costs, specifically the manufacture of supporting structures and their installation on site. Therefore, greater improvement is needed to **reduce capital costs, establishing easier and cheaper methods of manufacture.** Also, capital costs are higher when only a prototype or a single turbine is built; these costs are expected to be lowered when more than one turbine is built at a time. All in all, **tidal power is potentially economically feasible** as an energy source to penetrate the energy market.

The same methodology has been followed to compare the GHG emissions for the energy sources. The parameter that was to be compared is the quantity of GHG emissions that the generation of energy by a specific source produces. But it has been considered the whole life-cycle of this energy technology. This has shown that some renewable energies that were said to be clean and produce zero emission, only referred to the electricity generation phase. However, energy production always requires some previous steps, such as the construction of infrastructure or the harvesting of the fuel, and these stages actually produce harming emissions.

The values found in the literature correspond to the emissions of a certain plant, technology type or even country of a specific energy source. By contrasting and gathering several studies it has been expected to find a representative value for each energy source, with which it makes sense to make a comparison with the other resources.

According to the results, fossil fuels (coal, oil and natural gas) have the highest GHG emissions. These are between 500 and almost 1000 gCO<sub>2</sub>eq/kWh, and at least 80% of them are emitted in the fuel combustion. Hence, **the high production of emissions is inherent to these forms of energy.**

Regarding nuclear power and RET, their emissions of GHG are much lower than those of fossil fuels. According to the values found in the literature, emissions are around 100 gCO<sub>2</sub>eq/kWh for solar PV, and even lower for

nuclear power and the rest of renewables. For nuclear power, most of them are produced during the enrichment of the fuel; however they can vary depending on the process. Therefore, it means that by changing or improving this enrichment processes, emissions of nuclear power generation could be downsized.

With respect to renewable energies, they emit almost zero  $\text{gCO}_2\text{eq/kWh}$  in the actual generation of electricity. But according to the results, **they produce emissions in other stages of their life-cycle; mainly the construction of the infrastructure** (about 70% or 80%). Therefore it is not true the fact that RET do not emit GHG, even though their life-cycle emissions are much lower than those from fossil fuels.

In conclusion, the energy sources that are currently most used are fossil fuels. They are generally cheap and have the worldwide installed capacity to meet the current energy demand. However, the process by which fossil fuels release energy is their combustion, a process generates great amounts of GHG emissions. Furthermore, their resources are coming to an end. According to the results here presented, **some renewable energy technologies such as wind and tidal power have the potential to become a good alternative energy source**. Their costs are mainly driven by initial construction costs, and this stage is also the one emitting the highest amount of GHG emissions. Therefore, it would make sense to invest in developing technologies related to this area, such as construction and manufacturing methods, or installation procedures.

**One specific challenge regarding tidal energy is the development of more specific and cost-effective manufacture methods for turbine blades.** Even though they are very similar to wind turbine blades, they have some additional requirements due to the different environmental conditions. They are basically concerning the fact that the working environment of tidal turbines is water, which has a density around 800 higher than wind, and different flow velocities. This creates the need for more resistant blades, and then new manufacturing methods.

The goal of the second part of this thesis is to design a generic tidal turbine to study the manufacturing constraints and requirements in a future work. Therefore, the objective of the design is a detailed geometry of the blade. To perform the design, an approach using two open-source programs has been decided. With the input given, an optimization has been run in *HARP\_Opt*, which returned the chord and twist distribution for the optimal blade shape. Based on this shape, a blade has been modelled in *QBlade* with some adaptations. The result is a tidal turbine blade modelled with the NACA4418 foil along all the blade span, with a maximum chord of 0.8 m and a shear web located alongside the maximum thickness of each section. It operates at low rotational speeds to avoid cavitation, and is thicker than wind turbine blades. Tidal turbine blades must resist high loads, and therefore they are not hollow as

some wind turbines but rather reinforced. The designed blade has been tested under the simulation of loads produced by the different water flow velocities to ensure its durability.

However, the results here presented have some limitations. Regarding the evaluation part, it has only been done taking into account the values for LCOE and GH emissions found in the literature review. Therefore, it does not account for all types of technology for each energy source, or for all the possible power plants. The values here given try to state an average value for the cost and emissions of each energy source. These values aim to be representative for that resource, and are used only to make a comparison among them.

Regarding the blade design, many assumptions were made to develop the blade. The goal of this design is to study the geometry of a blade in order to establish the specifications for a manufacturing method. Hence, some assumptions have been made in order to fulfil the design. For the optimization in *HARP\_Opt*, estimations were made about the rotational speed and

Finally, there are essential parts to a turbine blade that have not been here considered, such as the connection to the hub. This additional part is normally manufactured separately and is therefore matter for another study.

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## Appendix

### A List of Figures

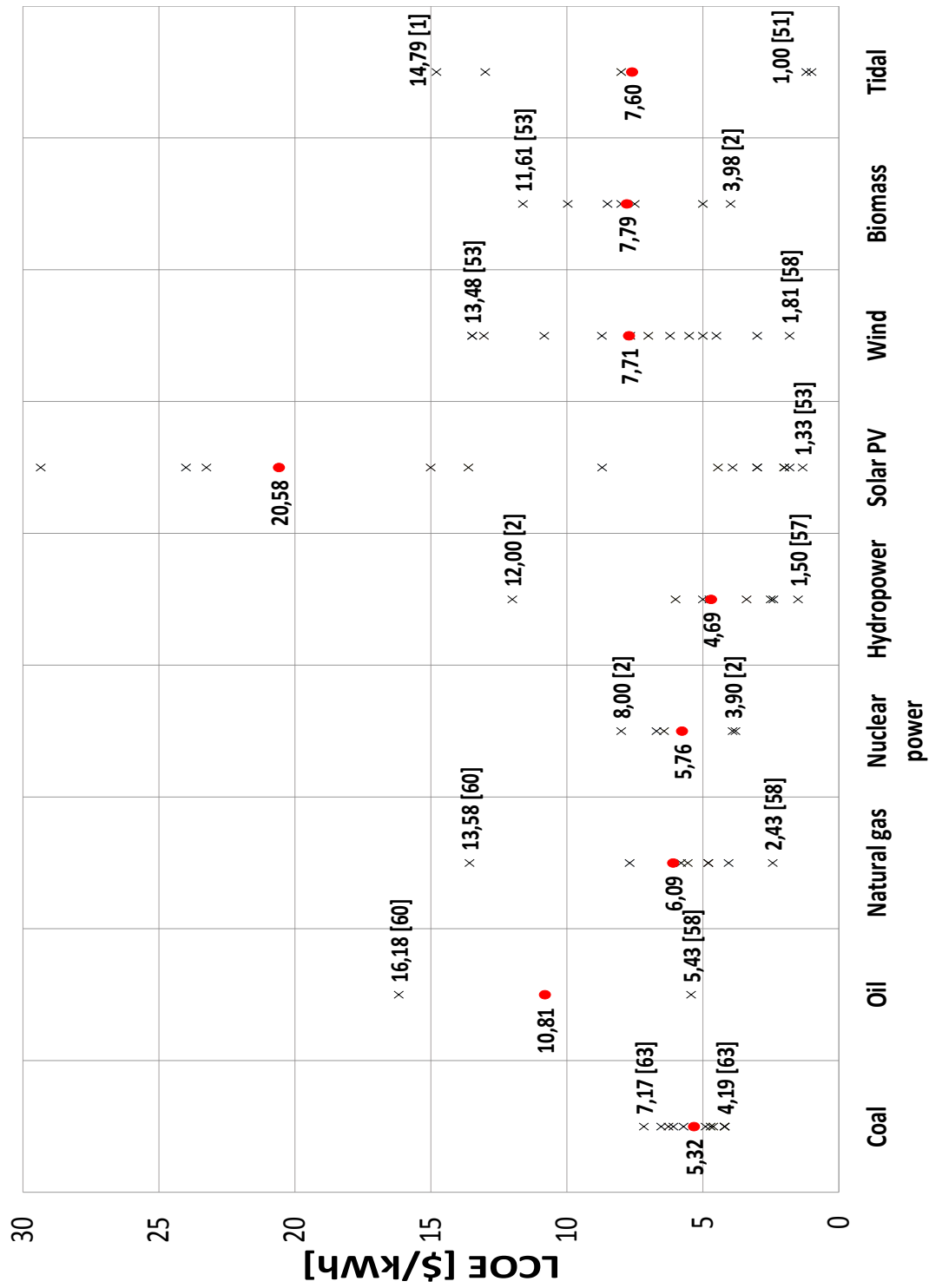
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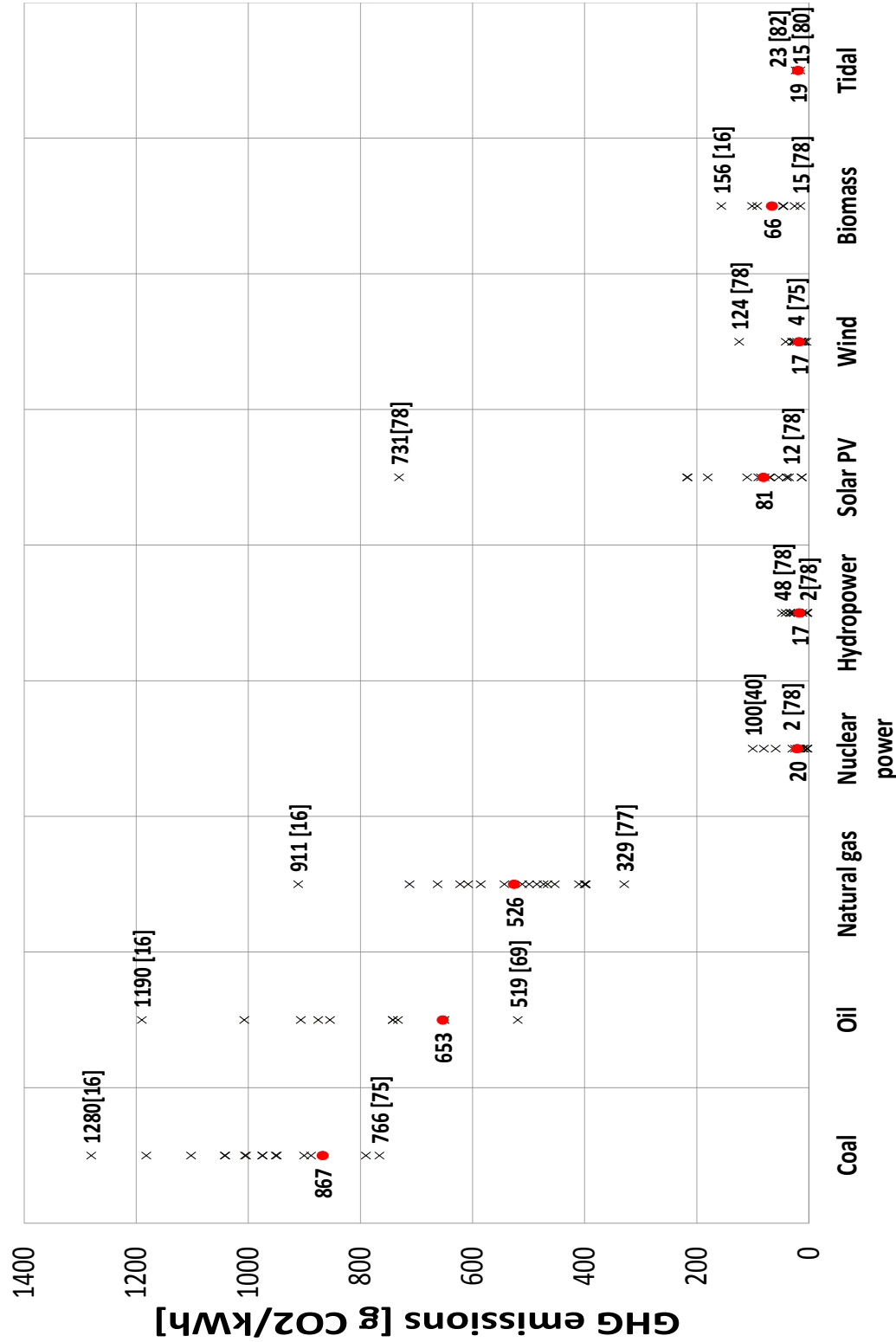
### C LCOE by Energy Source

Results of LCOE by energy source with the maximum and minimum values with its references.



D GHG Emission by Energy Source

Results of GHG by energy source with the maximum and minimum values with its references.





## E Blade Data

| Blade Radius<br>[m] | Blade Chord<br>[m] | Blade<br>Twist [deg] | Shell<br>Thickness [m] | Spar Location<br>[% chord] | Spar<br>Thickness [m] |
|---------------------|--------------------|----------------------|------------------------|----------------------------|-----------------------|
| 0,00E+00            | 2,00E-01           | 13,43                | 4,00E-03               | 0,25                       | 6,00E-03              |
| 6,00E-02            | 2,00E-01           | 13,43                | 4,00E-03               | 0,25                       | 6,00E-03              |
| 1,20E-01            | 4,00E-01           | 13,43                | 8,00E-03               | 0,25                       | 1,20E-02              |
| 1,80E-01            | 8,00E-01           | 13,43                | 1,60E-02               | 0,25                       | 2,40E-02              |
| 2,40E-01            | 1,00E+00           | 13,43                | 2,00E-02               | 0,25                       | 3,00E-02              |
| 3,00E-01            | 1,05E+00           | 10,27                | 2,10E-02               | 0,25                       | 3,15E-02              |
| 3,60E-01            | 1,05E+00           | 8,06                 | 2,10E-02               | 0,25                       | 3,15E-02              |
| 4,20E-01            | 1,00E+00           | 6,39                 | 2,00E-02               | 0,25                       | 3,00E-02              |
| 4,80E-01            | 9,54E-01           | 5,08                 | 1,91E-02               | 0,25                       | 2,86E-02              |
| 5,40E-01            | 9,01E-01           | 3,97                 | 1,80E-02               | 0,25                       | 2,70E-02              |
| 6,00E-01            | 8,49E-01           | 3,05                 | 1,70E-02               | 0,25                       | 2,55E-02              |
| 6,60E-01            | 7,96E-01           | 2,25                 | 1,59E-02               | 0,25                       | 2,39E-02              |
| 7,20E-01            | 7,45E-01           | 1,57                 | 1,49E-02               | 0,25                       | 2,24E-02              |
| 7,80E-01            | 6,95E-01           | 0,95                 | 1,39E-02               | 0,25                       | 2,09E-02              |
| 8,40E-01            | 6,46E-01           | 0,39                 | 1,29E-02               | 0,25                       | 1,94E-02              |
| 9,00E-01            | 5,99E-01           | -0,12                | 1,20E-02               | 0,25                       | 1,80E-02              |
| 9,60E-01            | 5,53E-01           | -0,60                | 1,11E-02               | 0,25                       | 1,66E-02              |
| 1,02E+00            | 5,09E-01           | -1,05                | 1,02E-02               | 0,25                       | 1,53E-02              |
| 1,08E+00            | 4,67E-01           | -1,50                | 9,34E-03               | 0,25                       | 1,40E-02              |
| 1,14E+00            | 4,27E-01           | -1,93                | 8,54E-03               | 0,25                       | 1,28E-02              |
| 1,20E+00            | 3,89E-01           | -3,36                | 7,78E-03               | 0,25                       | 1,17E-02              |
| 1,26E+00            | 3,53E-01           | -2,79                | 7,06E-03               | 0,25                       | 1,06E-02              |
| 1,32E+00            | 3,20E-01           | -3,22                | 6,40E-03               | 0,25                       | 9,60E-03              |
| 1,38E+00            | 2,88E-01           | -3,68                | 5,76E-03               | 0,25                       | 8,64E-03              |
| 1,44E+00            | 2,60E-01           | -4,14                | 5,20E-03               | 0,25                       | 7,80E-03              |
| 1,50E+00            | 2,33E-01           | -4,63                | 4,66E-03               | 0,25                       | 6,99E-03              |
| 1,56E+00            | 2,11E-01           | -5,14                | 4,22E-03               | 0,25                       | 6,33E-03              |
| 1,62E+00            | 1,89E-01           | -5,68                | 3,78E-03               | 0,25                       | 5,67E-03              |
| 1,68E+00            | 1,72E-01           | -6,25                | 3,44E-03               | 0,25                       | 5,16E-03              |
| 1,74E+00            | 1,56E-01           | -6,58                | 3,12E-03               | 0,25                       | 7,80E-03              |