POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

# Hydrogen production from offshore Airborne Wind Energy: system modelling and cost analysis

Tesi di Laurea Magistrale in
Automation and control Engineering - Ingegneria dell'automazione

Author: **Sofia Trombini**

Student ID: 969293
Advisor: Prof. Lorenzo Mario Fagiano
Academic Year: 2021-22

# Abstract

Hydrogen produced from renewable energy sources, also called green hydrogen, is considered a crucial element for ecological transition and decarbonisation. Its use in hard-to-abate sectors, such as air and marine transport, would replace about 10% of annual emissions of $CO_2$. From this perspective, this study focuses on the possible construction of a plant for green hydrogen production in offshore sites, evaluating the quality in four selected locations. The idea is to power the plant using AWE (Airborne Wind Energy) systems, an innovative method for wind energy production. The analysis develops starting from the main components necessary for the constitution of the plant: the AWE systems, the electrolyser, the compressor, the water desalination treatment, battery energy storage systems and storage. Then, the most suitable sizing for each element has been studied. Considering the importance of the economic factor in hydrogen market development, a cost analysis was subsequently carried out to obtain an indicative value of the cost per kilogram. The results showed that costs are aligned with or slightly above future cost forecasts. Therefore, this study uses AWE systems and combines them with the components required for operation in an offshore environment to advance the state of the art in the field of electrolysis and energetic transition.

**Keywords:** Airborne Wind Energy systems, Green hydrogen, Offshore wind energy, Renewable energy, Electrolysis

# Abstract in lingua italiana

L'idrogeno prodotto da fonti di energia rinnovabile, anche detto idrogeno verde, è considerato un elemento chiave per la transizione ecologica e la decarbonizzazione. Il suo impiego nei settori difficili da elettrizzare, come i trasporti aerei e marittimi, permetterebbe di sostituire circa il 10% delle emissioni annuali di $CO_2$. In tale ottica, questo studio si concentra sulla possibile realizzazione di un impianto per la produzione di idrogeno verde in ambiente offshore, valutandone la qualità in quattro siti scelti. L'idea è alimentare tale impianto utilizzando dei sistemi AWE (Airborne Wind Energy), un metodo innovativo per la produzione di energia eolica. L'analisi si sviluppa a partire dai componenti principali che sono necessari nella costituzione dell'impianto: i sistemi AWE, l'elettrolizzatore, il compressore, il trattamento di desalinizzazione dell'acqua, i sistemi di accumulo di energia a batteria e lo stoccaggio. Per i diversi elementi è stato studiato il dimensionamento più adatto al funzionamento della produzione. Tenendo in considerazione l'importanza del fattore economico nello sviluppo del mercato dell'idrogeno, è stata successivamente svolta una analisi dei costi per poter ricavare un valore indicativo del costo al kilogrammo. I risultati ottenuti hanno mostrato come i costi siano in linea o di poco superiori alle previsioni di costo future. Questo studio vuole quindi contribuire allo stato dell'arte con una ricerca nel campo dell'elettrolisi e della transizione energetica, facendo utilizzo di sistemi AWE e combinando le componenti necessarie per il funzionamento in ambiente offshore.

**Parole chiave:** Airborne Wind Energy systems, Idrogeno verde, Energia eolica offshore, Energia rinnovabile, Elettrolisi

# Contents

# 1 | Introduction

## Energy transition

The energy crisis and climate change are two of the most relevant topics in the current global debate. The Covid-19 outbreak has started to highlight the issues with the energy system, but it was the Ukraine crisis that made us aware of how reliant on fossil fuels our economy is. While this scenario emphasizes energy dependence on other countries and heightens economic instability, it can also provide new impetus for the energy transition, especially in Europe. The utilization of renewable resources and the adoption of innovative energy-related behaviours would allow greater environmental sustainability. At the same time, it would also provide greater energy security and market stability, making many nations less reliant on imported energy.

The 2015 Paris Agreement is the primary benchmark for emission reduction and improving energy sustainability. It aims to keep the temperature increment of this century 2 degrees below pre-industrial levels, with the strong recommendation of lowering it to 1.5 degrees. The idea would be to achieve net zero emissions by 2050, which means an emissions reduction of over 37 gigatonnes (Gt) annually [22]. However, this decrease is still an ambitious target, and the efforts made so far are still insufficient to accomplish this goal. According to IRENA's estimate [22], the Paris Agreement requirements can be met only through the development of six technologies: renewables, energy efficiency, electrification, hydrogen, carbon capture and storage and bioenergy coupled with carbon capture and storage (BECCS). Figure 1.1 illustrates how each of these technologies helps to lower $CO_2$ emissions.

Renewable energy sources (RES) will significantly boost energetic transition. Solar, wind, geothermal, hydroelectric, and biomass energy will substitute oil and gas since they are clean and not subject to exhaustion. Among the actual 7400 GW overall electricity installed capacity, only 2500 GW of generation capacity is from renewable sources. The most employed technology among them is hydroelectricity, which accounts for 47% of this total. However, solar and wind energy will mainly guide the energy transition in the next years. Of the 10770 GW required in 2030, solar PV will account for around 5200 GW,

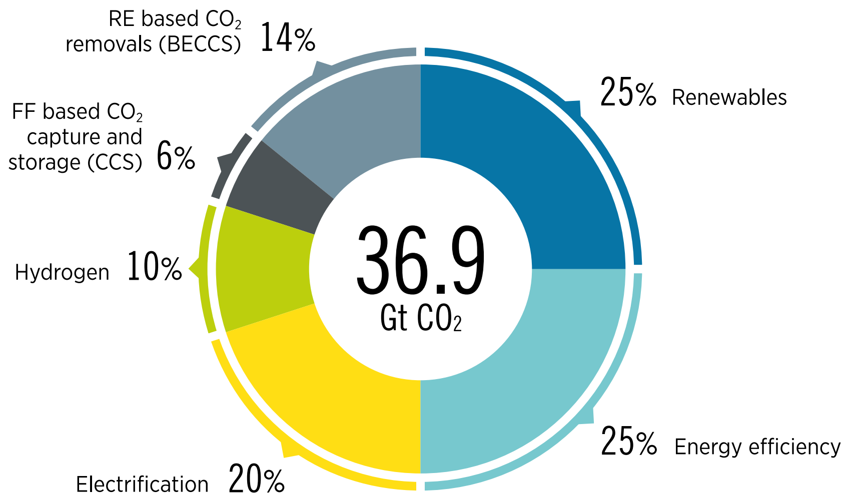



Figure 1.1: Contribution of the six technologies to emission reduction [22].

while wind energy for about 3300 GW.
The electrification of end uses will increase as a result of the decarbonization of electricity, enabling the electric running of services and other public and private activities previously powered by fossil fuels. If energy transition requirements will be satisfied, direct electricity usage in total energy consumption will climb from 21% in 2019 to over 50% by 2050 [22].
In addition to direct electrification, using green hydrogen will be essential for cutting CO2 emissions. This energy source would enable the indirect electrification of hard-to-abate industrial sectors, i.e., those where it is most challenging to cut greenhouse gas emissions, such as heavy industry, aviation, and shipping.
Alongside direct and indirect electrification, smart resource use and energy efficiency contribute significantly to the reduction of $CO_2$. This factor is crucial for modern structures, which should be energy-efficient, but also for the industrial sector, which can improve process and materials efficiency and apply a circular economy.
Finally, the carbon capture and storage techniques will also play an important role in emission reduction. Even if the best forecasts are met, fossil fuel use and $CO_2$ emissions from industrial activities are predicted to persist in a small percentage beyond the year 2050. Carbon capture and storage technologies will thus permit the removal of the $CO_2$ emitted in the atmosphere. By the way, it's important to underline that these procedures must be viewed as a support for the overall energy transition rather than the lone way to solve the energy crisis.

## Hydrogen economy

The attraction of hydrogen lies mainly in the possibility of use in hard-to-electrify sectors, such as transport, chemical or steel. Additionally, electricity does not work well in applications where molecules are needed as feedstock rather than an energy carrier. Hydrogen represents a viable solution instead. It's thus estimated that the parallel employment of hydrogen with electrification can contribute to reducing the emission of 10%. Clearly, hydrogen's potential remains as such only if it is produced via renewable energy sources (i.e. green hydrogen). Considering the importance of this topic, the G7 countries established the Hydrogen Action Pact (HAP) in May 2022 to collaborate on power-to-X, green hydrogen, and its derivatives.

Nowadays, about 70% of the hydrogen demand is used in refineries or for ammonia and methanol manufacturing, while the remaining part is employed as part of gas mixes. About 95% of this hydrogen total comes from steam-methane reforming and oil and coal gasification. However, these processes are far from sustainable. The emissions for the production are about 830 $Mt/year$ of $CO_2$, corresponding to 2.2% global annual emissions. Only 4% of all hydrogen comes from the electrolysis process and can be then regarded as green hydrogen. If we want hydrogen to be one of the leading technologies in energy transition, the production must entirely be the result of the electrolysis process, powered by electricity from renewable sources [21, 25].

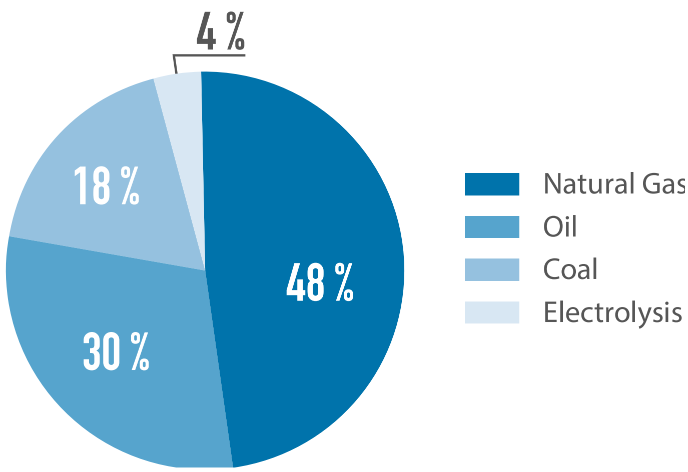
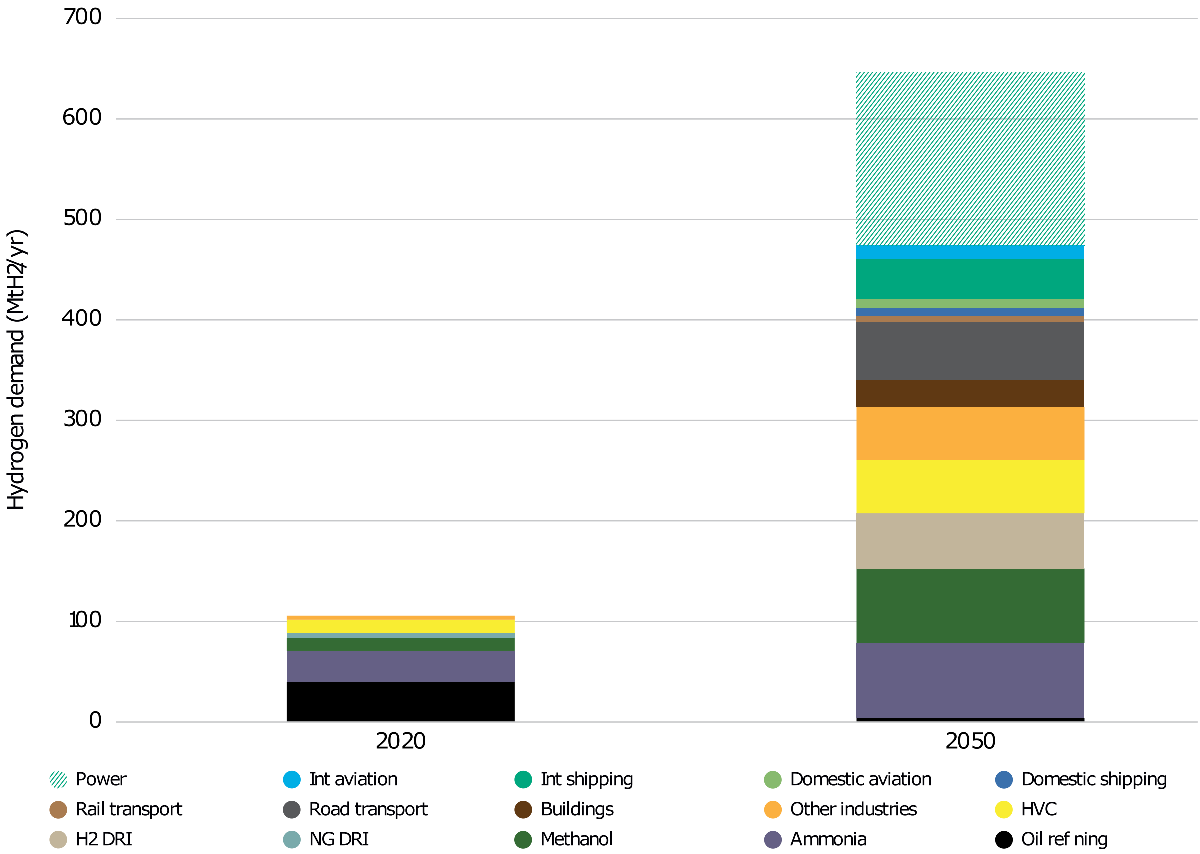



Figure 1.2: Hydrogen sources [21].

If the conditions outlined by the Paris agreement are followed, the use of green hydrogen in 2050 will increase by around six times compared to the current overall hydrogen consumption. As can be seen in figure 1.3, the demand will reach about 650 Mt/year.

The usage of hydrogen for oil refining will drop since fossil fuels will be gradually shifted away. Hydrogen for methanol and ammonia is anticipated to increase three to four times because of their use as fuels. However, the transportation industry will experience the most significant growth, and depending on whether hydrogen is employed for road, rail, ship, or aviation transportation, it will assume different forms, i.e., ammonia for ships and synthetic fuels for international aviation. The remaining portion will be employed in the power sector, mostly to offset RES fluctuations and as seasonal storage.




Note: Hydrogen demand for 2020 excludes hydrogen as part of the mix of of -gases for steel production. DRI = direct reduced iron; HVC = high-value chemicals; Int = international; NG = natural gas.

Figure 1.3: Hydrogen demand in 2020 and 2050 [25].

China is undoubtedly the country that will consume the principal hydrogen quantity, accounting for around 25% of global demand. India and the United States follow China in consumption, each accounting for 7% of the total hydrogen. However, the applications will be different between the two countries. While the United States will employ hydrogen mostly in the transport sector, India will use it primarily in steel production. All other nations will have lower consumption, but it's interesting to note that the top 10 countries will account for two-thirds of global production [25].

It is by no means simple to build a solid and well-developed hydrogen market. The hydrogen economy will only be able to consolidate thanks to significant worldwide coverage and huge investments, even though several governments have started programs to encourage this industry. Scaling up the hydrogen demand will be possible only through the parallel work of industry, governments and international associations.
The cost is one of the principal barriers to green hydrogen adoption so far. Currently, the price of hydrogen is quite unstable; on average, it costs around 5 €$/kg$, but it can go up or down by 1.5 €$/kg$ to the reference price. The key component to focus on for cost reduction is the electrolyser, i.e., the equipment required for the electrolysis process. In practice, production costs decrease is made possible by electrolyser increased employment, efficiency, and lifetime. The other crucial factor in the decrease in the cost of hydrogen is the reduction in the levelized cost of electric energy (LCOE). If these actions are taken, and the hydrogen market grows, the price of hydrogen could decrease to 0.75 to 1.25 €$/kg$ [23].

## Airborne wind energy

The use of renewable energy sources will play a significant role in the path toward a reduction in $CO_2$ emissions. These resources will displace fossil fuels in the majority of applications, also thanks to the electrification of several sectors. Wind energy, together with solar, will be the majorly exploited RES for green power production. The wind turbines currently dominates the wind energy sector. These devices are the most widely used, and ongoing research is trying to boost the rated power they can provide. However, airborne wind energy (AWE) is a promising new technology that has recently come into development in the wind energy field.
The AWE systems consist of an airfoil that operates at high altitudes and a tether that anchors this flying structure to the ground. The first investigation of the AWE principle appeared in the 1980s when Miles Loyd published the study Crosswind kite power (for large-scale wind power production) [27]. However, the study of such systems did not spread until the 2000s, when several researchers understood the potential of AWE systems. The first prototypes have already been created, and 2025 is the projected release date for the technology.
The most intriguing aspect of AWE systems is how they solve some of the issues with wind turbines:

- The cable used to connect the flying device to the ground, instead of using a tower as in wind turbines, makes it much easier to reach high altitudes (300-500 m above sea level). This working condition is crucial because high-altitude winds are more intense, constant and reliable. Because of this, production is much more constant, reducing the issue of activity intermittency common to renewable resources.

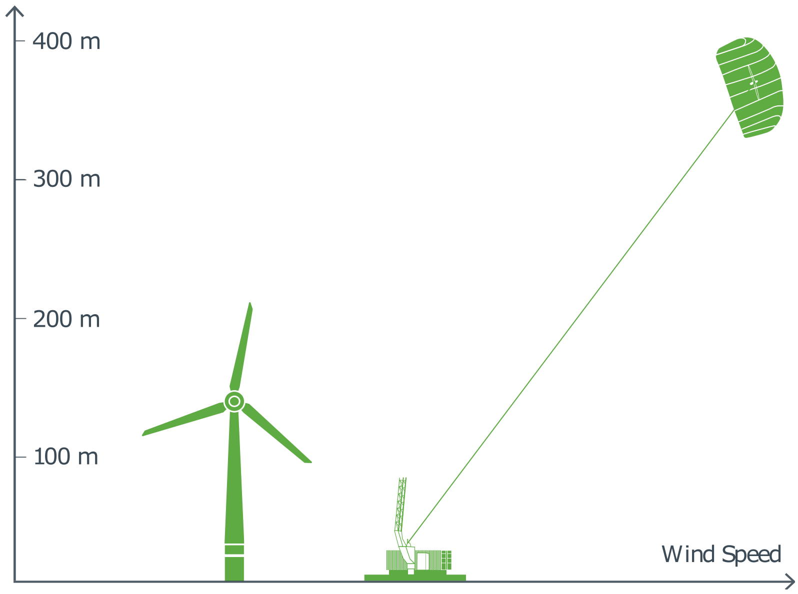



Figure 1.4: Working altitude for turbines and AWE systems. Adaptation from [1].

- The power generated by the AWE systems increases with the cube of the wind speed. As a result, even a slight increase in wind speed results in a substantial increase in the amount of power generated.
- The structure of AWE systems is simple, light and compact. Lightweight materials and ultra-durable fibres are used instead of energy-intensive materials like the steel of wind turbines. In addition, a simple cable made of lightweight composite fibre is used in place of the massive tower that holds the wind turbines. The result is a drop in the employed materials and a decrease in the structure's impact.
- The type of structure makes these systems extremely flexible. Their use can be adapted to multiple purposes and locations, both onshore and offshore. Contrary to wind turbines, AWE systems are thus much simpler to transport and install.
- The cost of turbines is still very high, despite their widespread. Additionally, due to the materials needed and installation costs, attempts to upgrade the turbines to have higher production will only contribute to the intensification of this problem. Given the previously mentioned features, AWE systems don't have these issues. As

a result, the costs are considerably lower.

All these elements support the belief that AWE systems are more promising than wind turbines, despite the system's complexity.

## Innovative aspects

The main original contributions of the thesis are:

- The use of AWE systems. This cutting-edge technology is a promising alternative to wind turbines for renewable energy generation. Due to the relatively recent development of technology, numerous types of research are underway in these years. The system is complex, so efforts usually focus on the technical and structural aspects. This thesis aims to contribute to the knowledge of this field, enriching studies on their potential and exposing their use for a different end.
- The installation of AWE systems in an offshore environment. Studies related to AWE are mainly focused on onshore locations, while the offshore application is only seen as a possibility in the distant future when the technology is fully established. This thesis intends to advance the field by demonstrating AWE's potential in the latter context, which has received minor investigation.
- The definition of the structure of the hydrogen plant from offshore AWE. This thesis studies the integration of the necessary components to use AWE systems, to produce and store hydrogen, and to desalinate seawater. In this context, the contribution refers to both the creation of novel strategies for the generation of green hydrogen as well as the integration of renewable resources with electrolysis plants.

## Thesis outline

- **Chapter 1 - System model** The model of the system is presented. Each plant component is described at first, focusing on different technologies needed for hydrogen production and relationships between the parts. Then some locations of interest and their selection criteria are reported.
- **Chapter 2 - Plant sizing and production** The energy consumption of each component is investigated, leading to some conclusions on plant sizing. Then, the wind intensity values in some locations are evaluated and the wind probability density function in computed. Finally, the hydrogen yearly production for each location is obtained combining wind speeds, energy production and consumption.

- **Chapter 3 - Economic analysis** After showing the costs of the single components, the hydrogen unitary cost is computed. A comparison between the different locations highlights which are the best sites for hydrogen production.
- **Chapter 4 - Conclusions and future developments** The final chapter presents the conclusions of the thesis and possible future developments and improvements.

# 2 | System description

## 2.1. Plant components

This chapter aims to define the structure of a hydrogen production plant using AWE in offshore sites. The idea is to start the analysis at a macro-level, identifying which components are needed and then focusing on single parts, going deeper into the details.
First, the objective is to produce green hydrogen, so a renewable energy source must power the plant. As already said in the introduction, this study centres on AWE systems, meeting this criterion. AWE systems will be the first elements to be analyzed. Then, it's necessary to include all the equipment related to hydrogen generation. The electrolyser, water treatment unit, compressor and storage are part of this group. Finally, a battery energy storage system (BESS) is added to fulfil potential emergency necessities.

Here a scheme of the plant components and their connection.

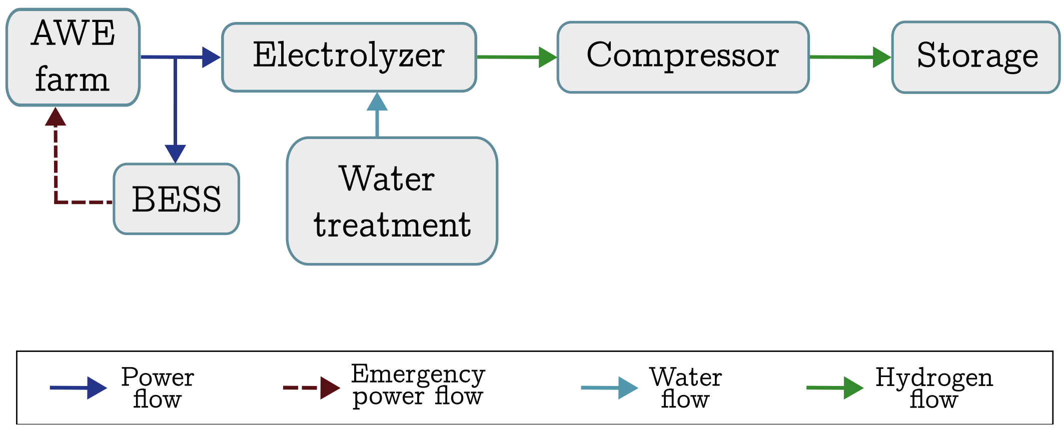



Figure 2.1: Plant scheme and interaction between components.

The single elements and the reasons for choosing them will be presented in detail in the following subsections.

### 2.1.1. AWE

The AWE systems are the core of this project, together with the hydrogen production. As already said, the AWE systems exploit the power of the wind for green energy production. In the introduction, we focused on innovative aspects of AWE systems and the several advantages of this technology against wind turbines. This section will present AWE technology and its functioning to acquire a general knowledge of how such systems work.

AWE systems are an emerging technology that intends to use wind energy for electricity generation. The idea is to use medium-high altitude wind to fly tethered airfoils connected to a ground station with a cable. Although the basic principle is always the same, multiple different AWE system types are being researched and studied. Figure 2.2 shows the classification of AWE configurations.

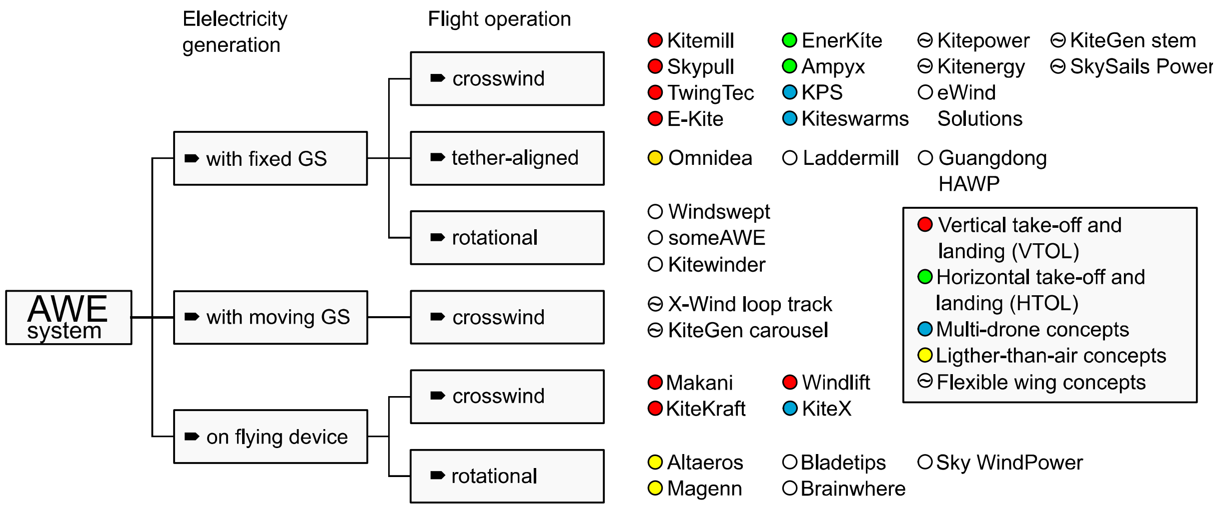



Figure 2.2: Classification of AWE concepts [36].

The first classification for the AWE systems concerns the technique employed for electricity generation. The are two main categories: on-ground generation systems, with fixed or moving ground stations and on-board generation systems.

The on-ground generation systems, as the name implies, possess a station on the ground equipped with an electric machine and power converters for electricity generation. They fly following pumping cycles in which they alternate traction and retraction phases. During the traction phase, the wind force pushes the kite, reeling out the connection cable from the drum on the ground. This action permits the activation of an electric generator and the consequent energy production. Instead, during the retraction phase, the kite is pulled back to its initial position to start a new cycle. This operation requires energy consumption for reeling in the tether to the winch. By the way, this phase is carried out when the kite is out of the wind to use the least amount of electricity and to have a positive energy balance at the end of the working cycle. Note that the passage from the traction to the retraction phase (and vice versa) is punctuated by a transition step. Figure 2.3 shows the cycle phases.

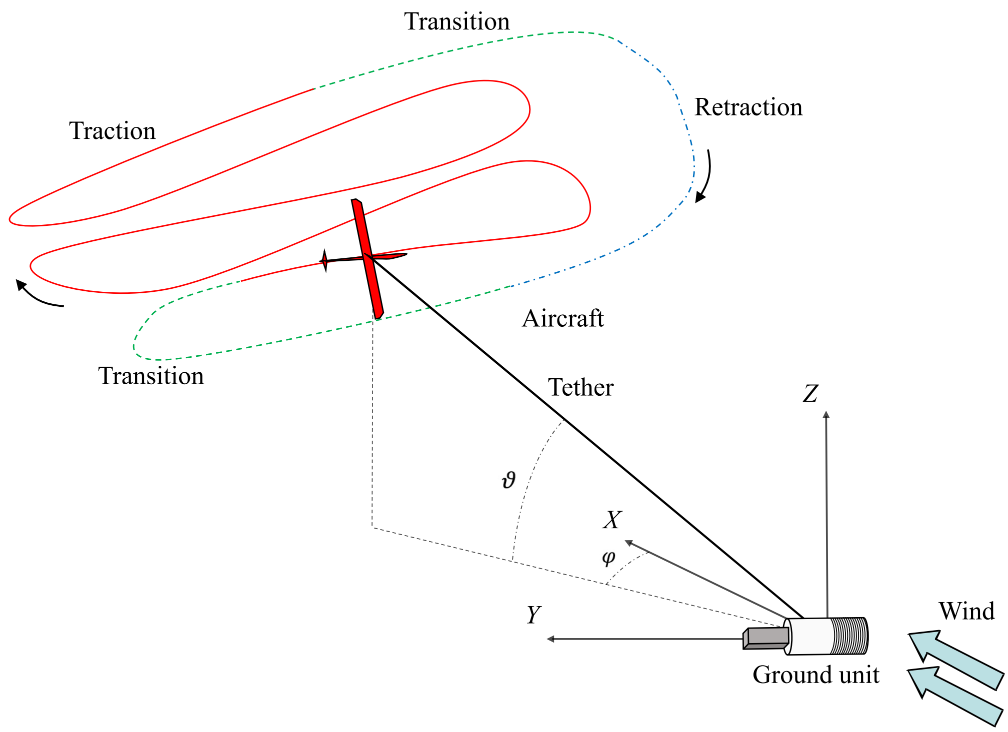



Figure 2.3: Production cycle of an on-ground AWE [11].

The on-board generation system is always a rigid aircraft equipped with small turbines on the wings. In this case, the generation phase is easier to manage since the tether is kept at a constant length while the onboard turbines produce energy exploiting wind power. The cable has a double function: on one side, it is employed in landing and take-off phases as in on-ground systems, on the other, it acts as a conductor for the ground transmission of the current produced. Note that wind turbines can be used also to facilitate the phases of take-off and landing [13].

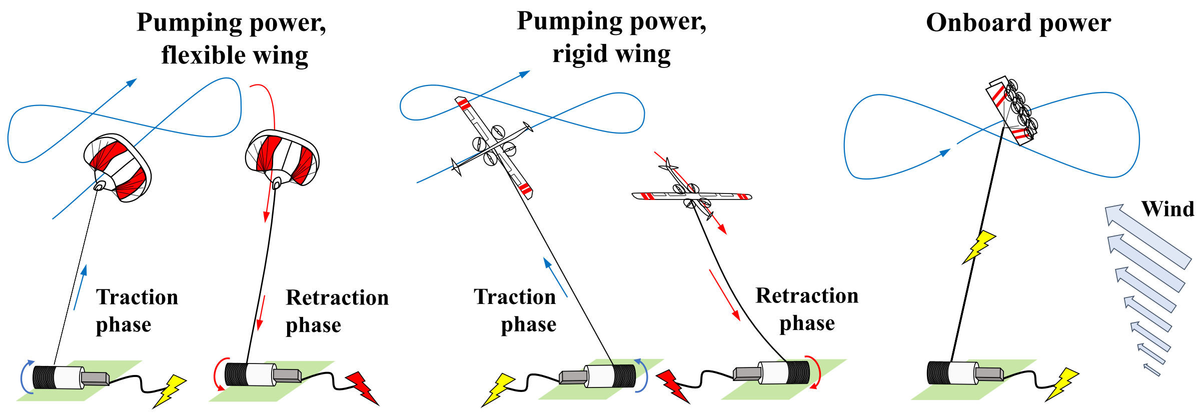



Figure 2.4: Comparison between on-ground and on-board generation systems [13].

The second step of the AWE system classification in figure 2.2 focuses on flight motion. There are three categories: flight perpendicular to the tether, also known as crosswind, flight aligned to the cable and rotational flight. However, the crosswind is the flight type on which most studies focus nowadays and which is nearer to industrialization. This type of flight implies that the kite's path is perpendicular to the wind flow, using the tether as a constraint. In this way, the aircraft's speed is greater than the wind speed, allowing good power production.
In addition to what was explained before, the AWE system can be classified following other criteria, such as the type of flying device (e.g. rigid aircraft, soft kites or quadcopters) or the methods used for take-off and landing (e.g. vertical or horizontal).

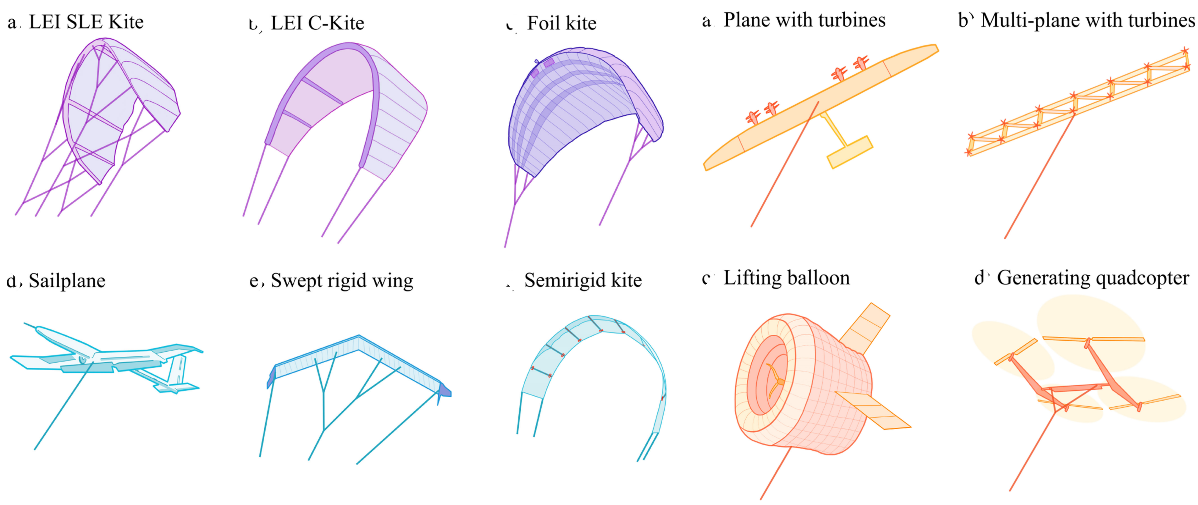



Figure 2.5: Different types of AWE systems depending on type of flying device. Adaptation from [8].

Note that all these configurations have huge potential but also present some disadvantages. Since AWE is a technology still in the R&D stage, all these structures need to be further investigated before understanding which are the most suitable conditions for their employment.

In addition to that, we can state that AWE systems could potentially be installed offshore; testing has already been done in recent years.
In 2019, Makani kite executed in the North sea one of the world's first offshore flights of an AWE system. The airborne system performed two flights: the first focused on take-off and landing, while the second showed a robust crosswind flight, even if the landing phase was not successful [14]. Alongside this attempt, the experience of Skysails also developed. Since the early 2000s, they have tried to exploit the potential of AWE in the maritime environment. Their idea was to employ the kite's power as a propulsion system for cargo vessels.
Beyond these two examples, AWE systems could be used in traditional offshore wind farms. According to the BVG Associates report [7], the AWE systems' employment in offshore environments could make it possible to exploit regions where wind turbines could not normally work. In addition, the costs for offshore AWE systems would be much lower than that of a classic wind farm. However, for such technology to be utilized offshore, it must first be developed in onshore areas.

Figure 2.6: Future implementation of offshore AWE farm [1].

### 2.1.2. Electrolyser

Hydrogen can be produced in several ways, as explained in the subsection dedicated to the hydrogen economy. At the same time, the only way to reduce emissions is to use RES to supply the hydrogen-making process. The leading production technology that satisfies this last condition is water electrolysis. The corresponding machinery is called a water electrolyser.
Water electrolysis is based on the simple chemical reaction expressed by equation (2.1), which splits water into hydrogen and oxygen [29].

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{2.1}$$

The electrolyser stack, which consists of two electrodes placed inside an electrolyte, is the core of the process. When electricity and water supply the cell, the reaction starts. On the anode side, water oxidises into $O_2$ and protons following equation (2.2).

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \tag{2.2}$$

Then, the cathode combines electrons and protons from (2.2), creating hydrogen:

$$2H^+ + 2e^- \rightarrow H_2 \tag{2.3}$$

The results of (2.2) and (2.3) are water-hydrogen and water-oxygen mixtures. These two will be subjected to separation, drying and purification to obtain $O_2$ and $H_2$. Note that the entire process is endothermic and non-spontaneous, which means that nothing happens if there isn't an energy supply [16, 18, 23].

The scheme in figure 2.7 is a general description of the electrolyser components. Note that single elements can change depending on the electrolyser technology.

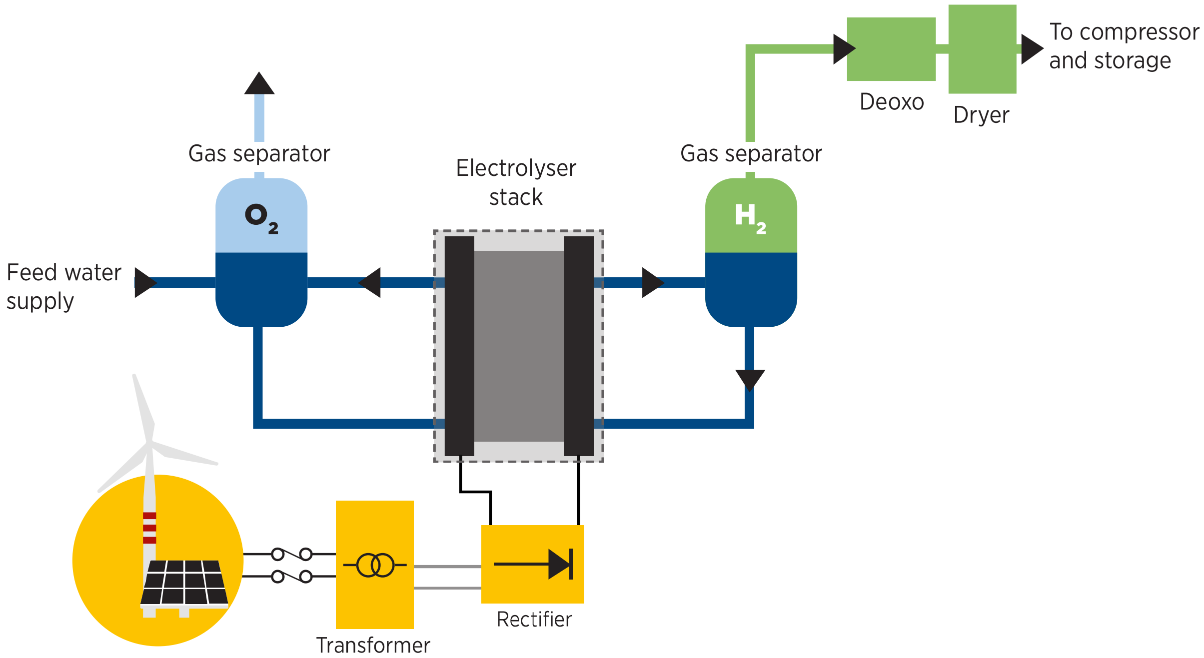



Figure 2.7: General scheme of electrolyser [23].

There are four main types of water electrolysis:

- polymer electrolyte membrane (PEM);
- alkaline;
- anion exchange membrane (AEM);
- solid oxide electrolysis cell (SOEC).

The main differences between these electrolysers lie in the stack cell (see figure 2.8), components material, operating temperature and pressure and stage of development. However, the water electrolysis basic working principle is common to all types [23].

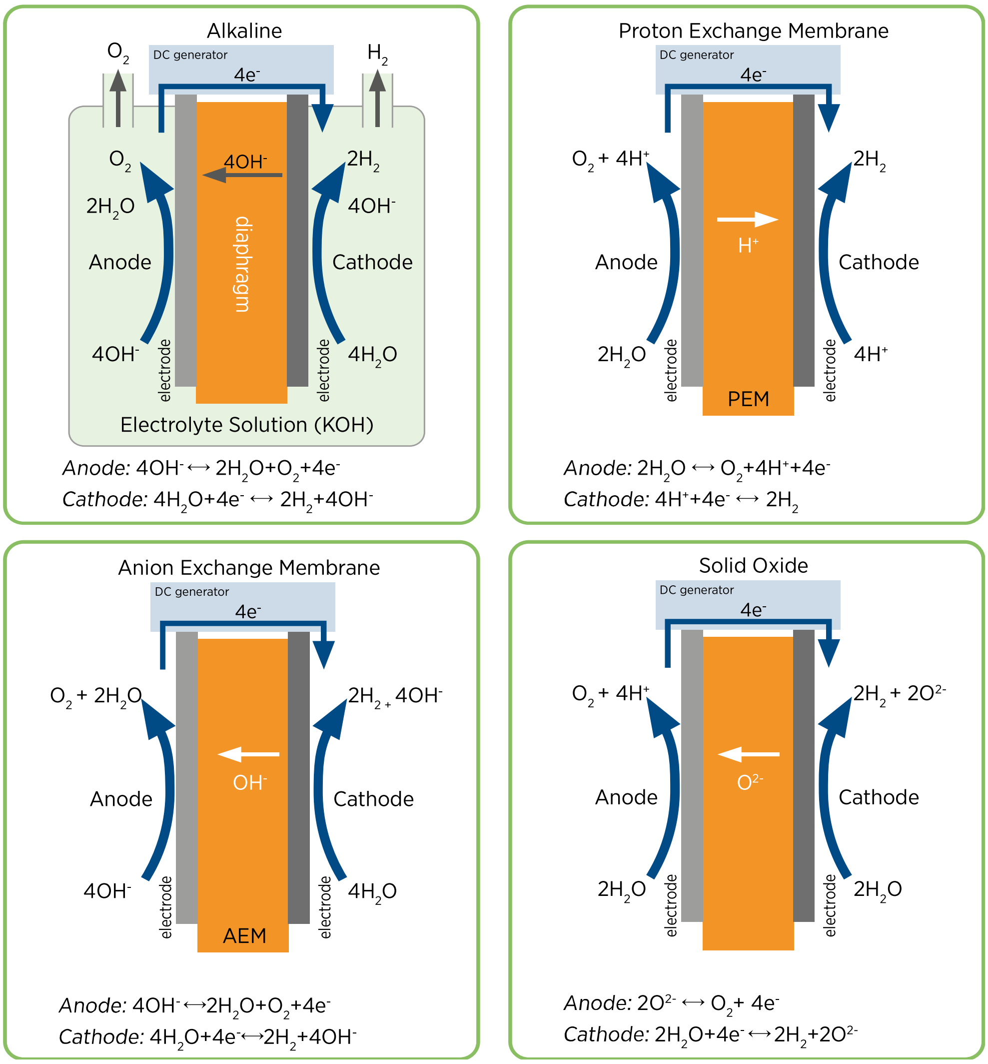



Figure 2.8: Cell stack for different types of electrolysers [23].

Alkaline and PEM electrolysers are both well-developed and commercial technologies, thanks to the numerous studies carried out since the nineteenth century. On the other hand, SOEC and AEM are both promising, but they are still at an R&D level. More analyses are needed before they enter into market [23]. That's why these two techniques were not considered in this study.

Focusing only on alkaline and PEM, the latter is much more expensive. By the way, PEM offers remarkable advantages compared to alkaline: higher current density, low cell area and compactness, better flexibility and efficiency, lower start-up time and greater $H_2$ efficiency (see table 2.1). Thanks to these features, it is possible to expect that this technology will become predominant in future. In addition, increasing demand for PEM electrolysers will lead to a decrease in the cost [28]. For this reason the electrolyser employed for this study is assumed to employ the PEM technology.

| | Alkaline electrolyser | PEM electrolyser |
|---|---|---|
| **Ions electrolyte** | $OH^-$ | $H^+$ |
| **Current density** ($\frac{A}{cm^2}$) | <0.45 | >1.0 |
| **Cell voltage (V)** | 1.8-2.4 | 1.8-2.2 |
| **Temperature (°C)** | 60-80 | 50-80 |
| **Pressure (bar)** | <30 | <80 |
| $\eta_E$ **(%)** | 60-80 | 80 |
| **Minimum load (% of NL)** | 10-40 | 0-10 |
| **Overload (% of NL)** | <150 | <200 |
| **Cold start up time (min)** | 15 | 5-10 |
| **Warm start up time (min)** | 1-5 | <0.2 |
| **Cell area** ($m^2$) | <4 | <0.13 |
| $H_2$ **purity (%)** | 99.8 | 99.999 |
| **Stack lifetime (h)** | 60000-90000 | 30000-90000 |
| **System lifetime (year)** | 20-30 | 10-20 |
| $\eta_E$ **degradation (%/year)** | 2-3 | 3-5 |

Table 2.1: Main parameters of alkaline and PEM electrolysers [28].

### 2.1.3. Water treatment

Water is the input ingredient for hydrogen production, together with electrical power. The electrolyser requires water as pure as possible for the proper functioning of the process. The presence of impurities can affect the stack lifetime and the hydrogen quality. The maximum acceptable value of total dissolved units (TDS) is 0.05 ppm (note that the level of purity can change depending on electrolyzer) [23, 29].Therefore water has to be treated before entering the electrolyser.

The strategies that can be adopted are two:

- use of fresh water with a purification treatment;
- use of seawater with a desalination system.

The availability of fresh water is limited since the plant is located offshore. This alternative would imply water transport from the ground to the platform, either with an infrastructure connecting the two sides or shipping water. The former option would entail significant work because the plant is at least 20 km from the coast, while the latter doesn't ensure a sufficient supply for functioning. The freshwater solution would be much more suitable for an onshore site. On the other hand, seawater is always accessible and fits the requirements of the electrolysis process if correctly pre-treated. In addition, this solution doesn't affect water availability in water-stressed regions. For this plant, the choice falls on this last option.

The desalination process is mature and widely used. The essential human need for potable water has meant a deep desalination study through the centuries. Many arid regions still don't possess enough fresh water or their resources are extremely limited. Considering that this problem is likely to increase due to climate change, this technology will probably be continuously up-to-date and improved. Today the most commonly used method for desalination is reverse osmosis (RO), which guarantees high purity levels [15].
If we want to understand RO, it's necessary to recall the concept of osmosis. This principle states that when two solutions with different concentrations are separated by a semipermeable membrane, the less concentrated (dilute) solution naturally flows to the more concentrated one. The membrane can be crossed only by some species, causing the isolation of specific substances. However, if we apply a pressure difference on the two sides of the membrane (i.e. force application on the most concentrated solution), the flow direction is inverted. This phenomenon is called reverse osmosis and it is applied in desalination [10, 15].

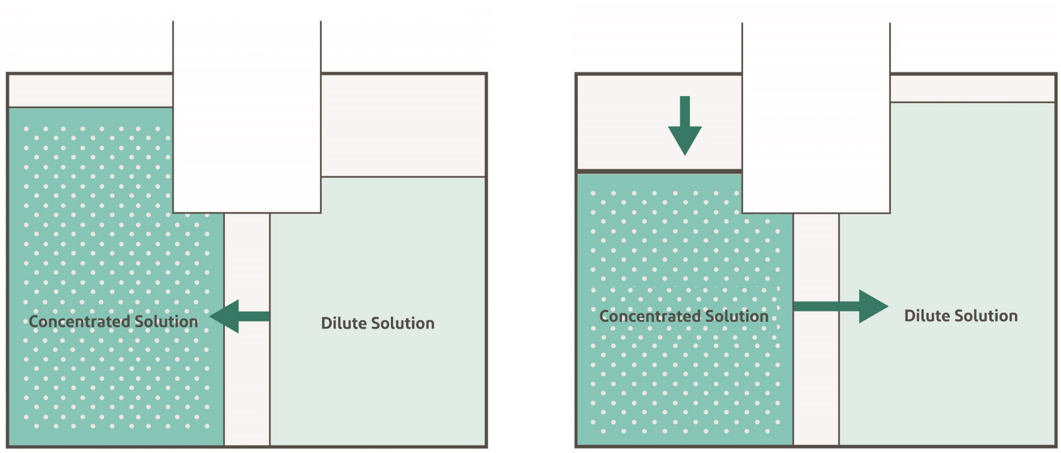



Figure 2.9: Osmosis and reverse osmosis principles, respectively [10].

When dealing with seawater reverse osmosis (SWRO), the container's sides are fulfilled with seawater and pure water. In this case, the membrane is permeable to water, but not to salt and other dissolved substances. The membrane will transform saline water into a pure one, working as a filter.

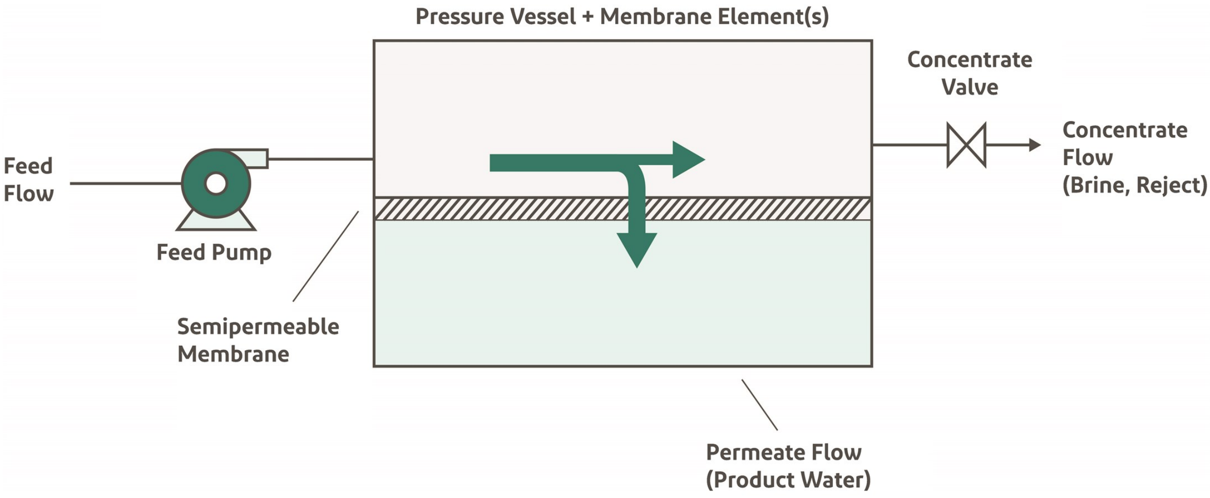



Figure 2.10: General scheme of reverse osmosis process [10].

A concentrated valve is placed at the exit of the "salt side". Its role is to control the feed water flow and the quantity of permeate (i.e. pure water) and concentrate (i.e. salt and rejected material) obtained. It works as feedback for process.
In addition to the RO module, which is the kernel of the system, the process requires some other elements:

- The water abstraction system pulls water from the sea to the platform.
- The pre-treatment system increases efficiency and membrane lifetime. It optimizes water flow, quality and cost and maintenance of the membrane. The structure of this process changes depending on the water source, composition and application.
- The pumping system creates pressure and reverses the osmosis process.
- The energy recovery system recovers up to 40% of the energy. The pressure of the concentrate stream is transformed into electric energy using a turbine or a piston.
- The control system oversees the plant operations and maintains safety [10, 15].

### 2.1.4. Compressor

After electrolysis completion, hydrogen is available but still not ready to be sold. Whatever the storage type, hydrogen needs to be compressed for transport. That's because hydrogen has a low volumetric density at standard pressure and temperature, despite its high energy density. Consequently, hydrogen takes up significant storage space, differently from other energy sources. The only way to increase volumetric density and facilitate the transfer is compression. Figure 2.11 shows this phenomenon.

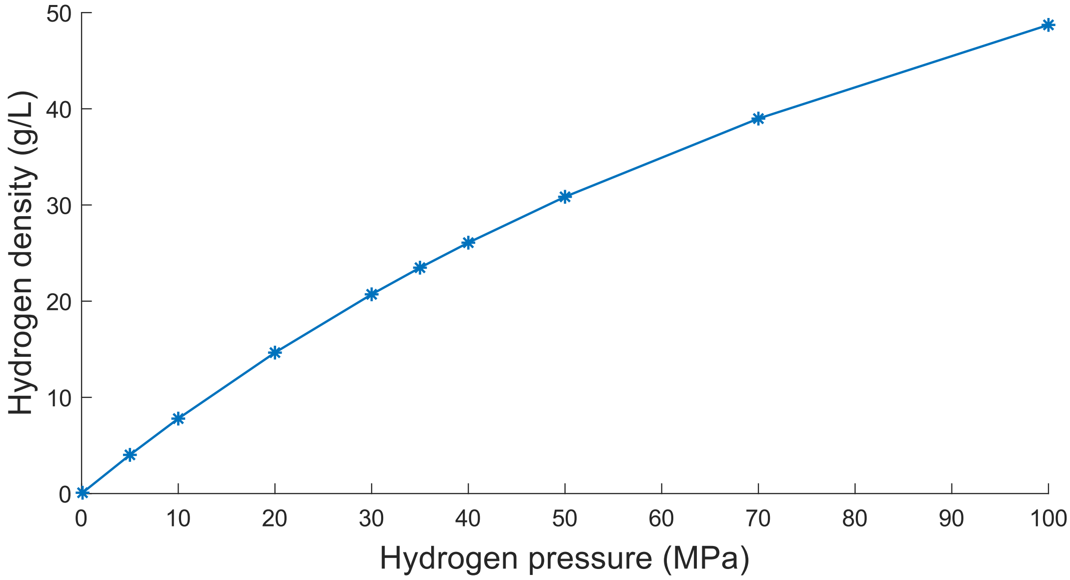



Figure 2.11: Density increase with pressure, at 20°C [40].

The operation of the compressor is dependent on the type of storage. As explained in next subsection 2.1.5, the choice for this plant is gaseous storage. Especially, type I tanks are the container chosen for hydrogen. The characteristic pressure for these tanks is around 200-220 bar, so the compressor has to increase pressure till this value.

There are two main categories of hydrogen compressors:

- Mechanical compressors directly convert mechanical energy into gas energy. They include the reciprocating, diaphragm, linear and liquid compressors.
- Non-mechanical compressors are all the ones not inside the first group. In the majority of cases, they are custom designed for hydrogen applications. They comprise cryogenic, electrochemical, metal hydride and adsorption compressors.

Non-mechanical compressors are promising but newer and still in development. Contrary, mechanical ones are well-studied and the most used today [31]. So the compressor for this plant is in this category. In particular, the choice is for a reciprocating compressor since it's a mature technology and meets the pressure requirements.

Reciprocating compressors are positive displacement compressors, which means that the motion of a piston decreases the volume of the hydrogen and consequently increases the pressure of the gas. The system exploits the rotational motion of a crankshaft supplied with electrical energy. A rod connects the shaft and piston and converts the rotational motion into a linear one. In this way, the piston moves up and down in the chamber. When the piston goes down, it creates a sort of vacuum. So the inlet valve opens and the gas enters the compartment. Then, the piston starts moving up and compresses the gas. Once the pressure reaches the desired value, the outlet valve opens and the gas is released [31]

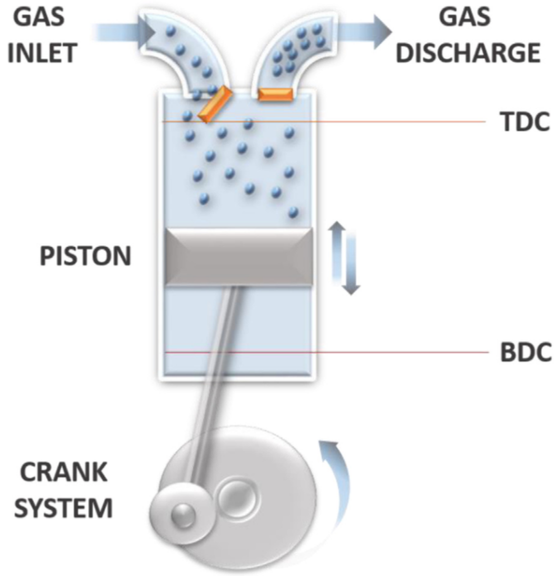



Figure 2.12: Reciprocating compressor [31].

Note that reciprocating compressors can appear in single-stage or multistage configurations. The latter is generally employed when the pressure value to reach is high. The first stage increases the pressure at an intermediate level. Then the others will bring pressure on the desired value. This study considers a two-stages reciprocating compressor since the final pressure is not particularly high (220 bar).

### 2.1.5. Storage

After hydrogen production, the gas has to be stored, waiting for its employment or sale. As explained in subsection 2.1.4, hydrogen has a particularly low density, which makes it unsuitable for transport if it does not occupy large amounts of space. That's why storage is one of the keys to hydrogen industry development. The proper storage techniques would pave the way to hydrogen commercial expansion.

Storage types can be divided into three groups [3]:

- physical storage, which divides into gas and liquid;
- chemical storage, which includes metal hydrides and chemical hydrides;
- adsorption.

Chemical storage and adsorption are still at an R&D level. These technologies will probably dominate the future market thanks to their promising feature. However, some issues, such as layout, load ranges and cost, do not allow their expansion today, unlike physical storage which is much more mature and widespread. In addition, we can say that there is no perfect way to store hydrogen, but that there are only ways more suitable than others depending on the situation.
Since hydrogen has to be transported from an offshore platform to the ground, this study should consider a type of storage suitable for handling. The two final alternatives were gas or liquid hydrogen storage. The choice was to compress gas since it is an established and complete technique. The gas tanks guarantee transport security up to 200-220 bar, but the storage method is also applicable if future development will admit higher pressure values. In this case, it will be enough to add stages to the compressor and use types of tanks suitable for higher pressures. This demonstrates the scalability of the technique, which was a plus when choosing between gas and liquid. In addition, liquid hydrogen would require the use of an additional instrument: the liquefier. However, liquid storage remains valid and future studies may investigate this other opportunity.

The second choice is the tank type. There are four types of vessels: type I, type II, type III and type IV (see figure 2.13). They mainly differ in the material, composition, maximum pressure value and cost. This differences are highlighted in table 2.2.

| | **Material** | **Maximum pressure (MPa)** | **Cost performance** |
|---|---|---|---|
| **Type I** | Metal (steel or aluminum) | 50 | ++ |
| **Type II** | Metallic liner wrapped with fiber resin composite | Not limited | + |
| **Type III** | Plastic or metallic liner wrapped with carbon fibres embedded in a polymer matrix (mostly metal liner) | <45 | - |
| **Type IV** | Plastic or metallic liner wrapped with carbon fibres embedded in a polymer matrix (mostly polymer liner) | <100 | - |

Table 2.2: Main parameters and differences between gaseous hydrogen tanks [4].

Considering that the maximum pressure safety value for tanks and tube trailers is 220 bar (22 MPa), the type providing the best value for money is the type I. Whereas they are also the easiest to find on the market, they are the ones chosen for this plant.

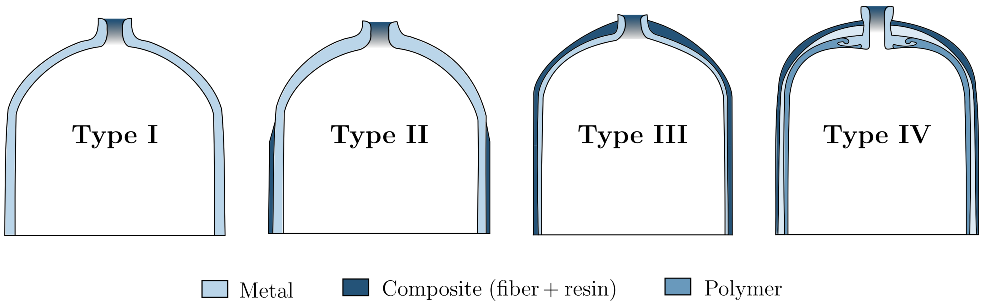



Figure 2.13: Types of pressure vessels [37].

### 2.1.6. BESS

BESS are systems for the momentary accumulation of energy. The idea is to use electricity produced by the AWE system to recharge the BESS and then use the latter to supply plant components in critical periods.

The main reason that led to the introduction of BESS is related to AWE systems. As explained in subsection 2.1.1, four phases are composing the AWE system cycle: traction, retraction and two transition phases. During the retraction phase, the system requires energy to retract the cable. In most cases, the traction phase should produce more energy than the amount required for the subsequent retraction. In addition, when the system is composed of more than one element, the AWE systems are dephased to compensate for the reciprocal retraction phases. In this way, the system should self-compensate and the retraction phase should not require more energy than available in the overall plant. By the way, the system includes a BESS to intervene if the AWE system can't autonomously supply the retraction phase. Then, safety and efficiency are increased.

Note that the use of BESS for problems of self-compensation in offshore farms is poorly explored today. Further investigation of this topic may be the object of future studies.

## 2.2. Plant locations

Wind energy is the key to plant productivity. The better the wind speed conditions, the greater will be the hydrogen production over the year. Therefore, the choice of the production site is of fundamental importance.

The offshore sites analysed by this study are four:

- Hornsea One wind farm (England);
- Viana do Castelo wind farm (Portugal);
- Marsala coast (Italy);
- Olbia coast (Italy).

The plants' positions are selected depending on some criteria. Firstly, the average wind speed needs to be above $6/7\ m/s$. This value guarantees a power production equal to half of the AWE system's nominal power production. The observance of this rule is essential because the wind is the power source of the entire plant. Not enough wind speed means no AWE system functioning and hence no hydrogen production. Seeing how important this element is, all the sites respect this criterion. Figure 2.15 shows the mean wind speed in Europe and in the offshore locations of interest.
The first two sites correspond to already existing offshore wind turbine farms. The Hornsea One is 120 km far from the Yorkshire coast. It was the world's first offshore wind farm with a capacity greater than 1 GW. Thanks to its 174 turbines (7 MW each), it generates enough green energy to power over 1 million UK homes. The WindFloat Viana do Castelo farm is 20 km from the Portuguese coast. It has a 25 MW and it can supply 60000 families per year. These locations have been chosen because they guarantee plant productivity in terms of wind power, being existing wind farms. In this way, we can guarantee energy generation and possible problems in hydrogen generation are not due to

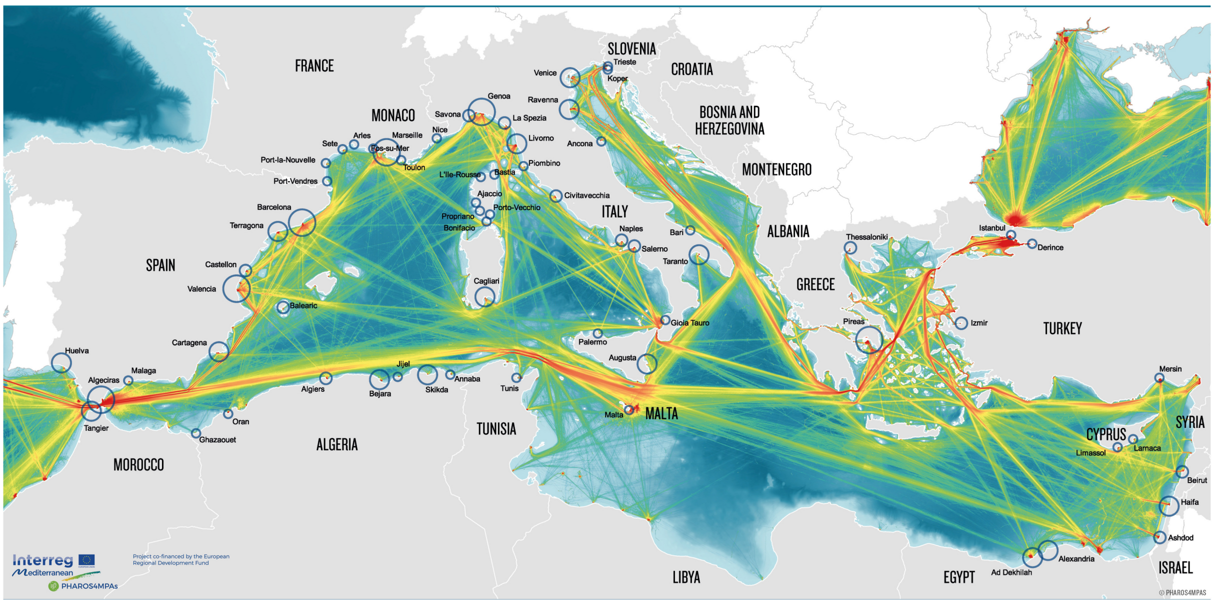



Figure 2.14: Maritime traffic in Mediterranean sea [38].

scarce wind speed.

Marsala and Olbia sites meet different criteria than the previous two places. Wind speed data were matched with a ship traffic density map in the Mediterranean Sea to find which locations have potentiality in terms of productivity and ease of being reached by ships already sailing. The idea would be to transport the hydrogen produced using cargoes that are sailing for other purposes, so as not to overload ship traffic and reduce emissions. So the offshore plant has to be placed in a hub crucial for marine traffic. The stretch of sea off Marsala includes the most important trade routes of the Mediterranean Sea and offers

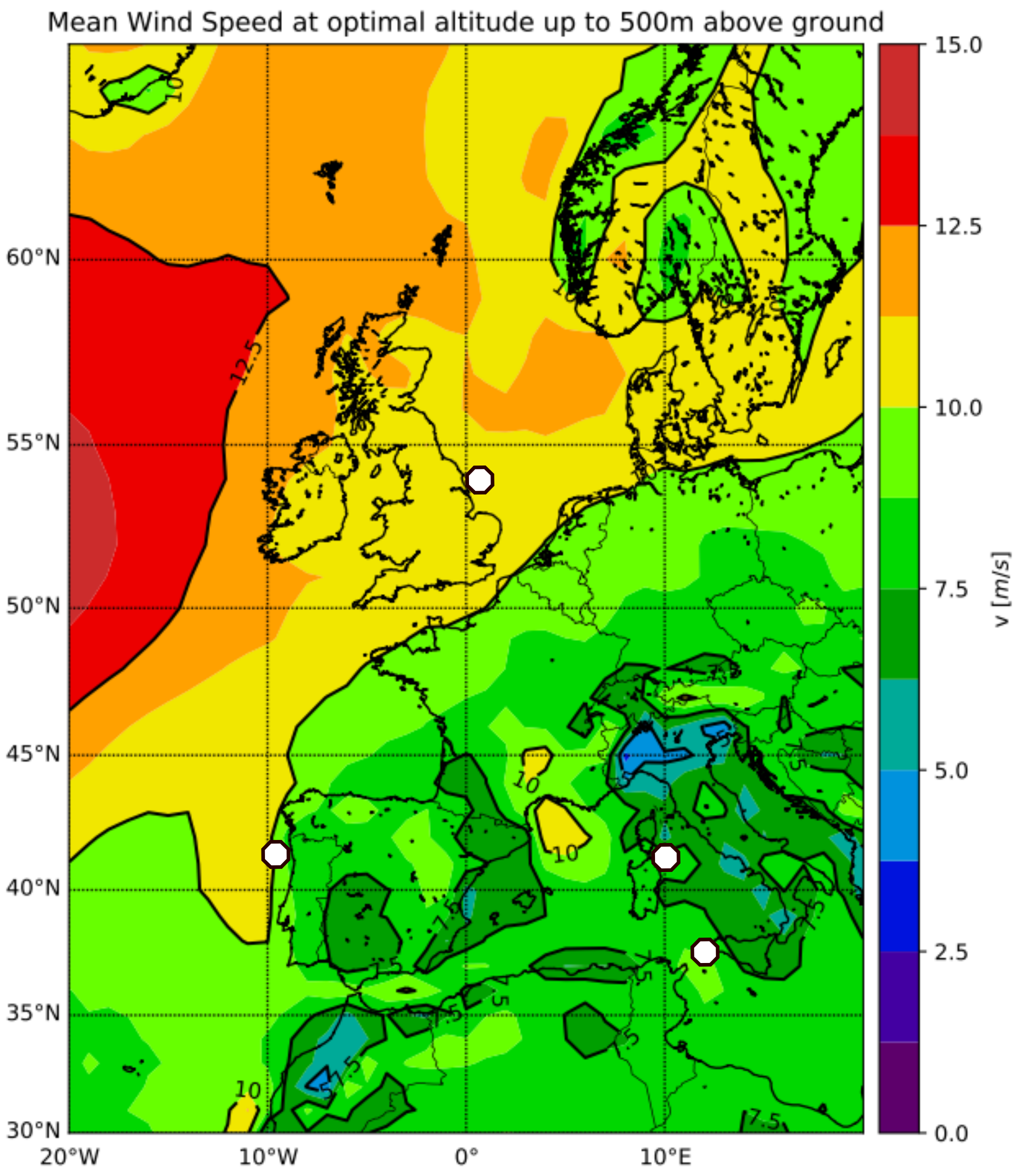



Figure 2.15: Wind speed mean at optimal altitude up to 500m. Selected locations highlighted in white. Adaptation from [5].

significant wind speeds. At the same time, Olbia is one of the most important ports of Sardinia, together with Cagliari port. The ships' passage is continuous, making this sea tract ideal for hydrogen transport both to Sardinia and to other destinations far from this island. The average wind speed is smaller than the other three locations but sufficient to respect the limit previously imposed. Note that these locations were involved in feasibility studies for offshore wind turbine farm installation, both with positive results [9, 39]. This strengthens the goodness of Marsala and Olbia as production sites.

The choice of these four locations is aimed to to build a complete study of the project. The intent is to analyse the hydrogen production plant quality and at the same time, we want to evaluate the possibility of installing offshore AWE systems in spots not yet exploited.

# 3 | System model: plant sizing and hydrogen production

## 3.1. Working assumption

Before starting the chapter, it's important to highlight some working assumptions for the project.

- All the component ratings considered in the project are considered as real numbers. This means that we don't pick the specific component size choosing between the ones available in the market, but we select the dimension as the one resulting from the calculus. By the way, we ensure that the size is comprised in the range of the existing ones (or that will exists in 2040). A solution based on commercial products can then be either obtained by taking the closest value on the market that satisfies all constraints, or by commissioning ad-hoc products. Moreover, many subsystems are already obtained by stacking together smaller modular units until the desired rating is achieved, thus making this assumption reasonable.
- Hydrogen is stored inside tanks directly on the platform. Then, vessels pick up these tanks and take care of hydrogen transport on land. The assumption is that the passage of merchant ships is such to ensure the shipping of hydrogen produced in a day. This decision was taken considering a significant development of the hydrogen market. It's also a choice to limit the space dedicated to storage and, therefore, to reduce the size of the offshore platform.

Note that the measurement unit for unitary consumption is $kWh/kg$. In addition, note also that the production sites can be identified both by number and by name, using the following numbering:

1. Hornsea One;
2. Viana do Castello;
3. Marsala;

4. Olbia.

## 3.2. Components' sizing

The description of the plant doesn't only deal with components' functionalities and reciprocal relationships, but it is also associated with the sizing of the elements. Assigning the right dimension to each plant part is of fundamental matter. If a component is underpowered, the workflow may be limited to the nominal power of this machinery, causing drops in production and profit. On the other hand, when a component is oversized, its potential may not be exploited. As a consequence, the workload would not justify the investment in such powerful equipment. In this case, the loss would be mainly in terms of earnings.
In this project, AWE production states how much power is at the disposal of the entire hydrogen production process. Therefore, the sizing of this system depends totally on the AWE system. The available power will be redistributed between the other part of the plant: electrolyzer, compressor and water treatment.
The component sizing procedure doesn't deal only with the AWE system's delivered power, but it's also a matter of energy consumption of the single elements. The knowledge of how much energy each component uses is fundamental both for the evaluation of the quantity of hydrogen produced and for the plant's power needs. That's why each component consumption is evaluated during the project.

The following subsections will focus on the energy consumption of single components and possible choice in size selection.

### 3.2.1. AWE

As explained before, the AWE system is the RES for the power production of this plant. So, for this element, the evaluation is not in terms of power consumption but production. The AWE system unit base that is considered is a AWE system with a 1 $MW$ average power over the production cycle. The power peak is around three times the average power and the mean power during the generation phase is about 1.4 times the average power over the entire cycle. Figure 3.1 shows the power curve of this AWE system, depending on the wind intensity. As we can see, when wind speed is between 0 and 5 $m/s$, the AWE system doesn't provide power to the system. The AWE system doesn't take off since the wind is not sufficient. The system starts its operation when the wind speed is around 5 $m/s$. From this point on, the power grows from 0 to the nominal value $P_{AWES_{NOM}}$ ($\sim 1.1MW$), reached when the wind speed is around 10 $m/s$. After this value, power remains constant.

Note that when the intensity is greater than 25 $m/s$, the AWE system is assumed to land for safety reasons. So, the production above such a cut-off speed is zero. At the current state of the art, the speed limit for a AWE system's correct functioning is greater than 25 $m/s$, but this study wants to make a conservative estimate by choosing the same cut-off speed as that of conventional wind turbines. Any other power produced at higher speeds can only improve the final balance.

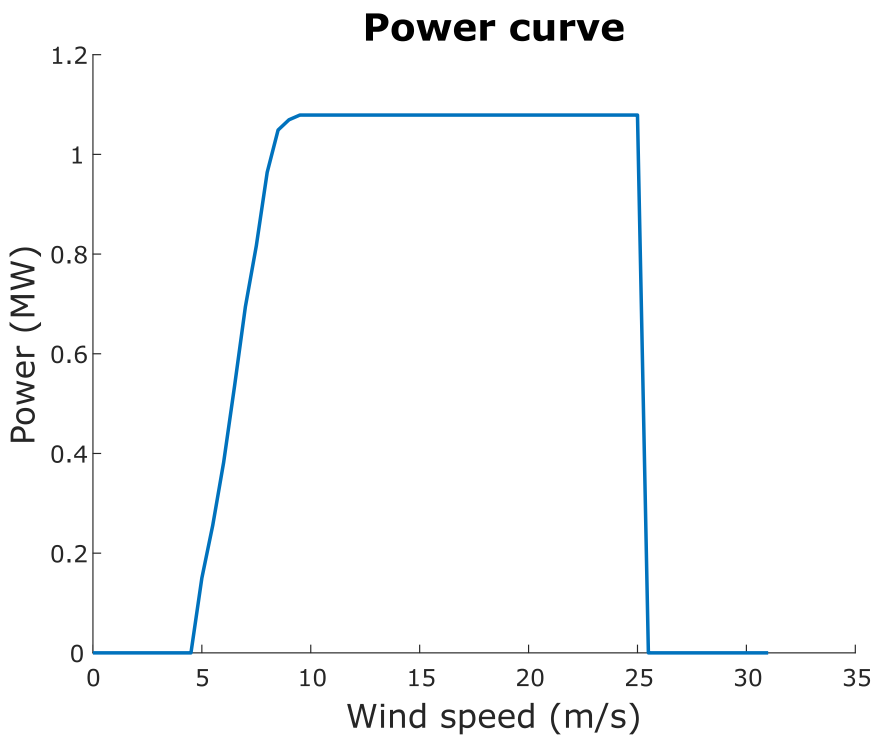



Figure 3.1: Power curve of a 1 $MW$ AWE system.

The idea of this project is to create an offshore wind farm. So, the location will comprise more than one installed AWE systems. The base case includes two AWE systems of $\sim 1MW$ each, hence with a total nominal power of $\sim 2MW$. Then the study will analyse other cases incrementing the number up to 30, considering a step size of 2 base units. Given what was explained before, table 3.1 shows all the considered cases for AWE sizing, specifying the number of AWE systems and the nominal power. Moreover, knowing that the estimated surface occupation for 16 AWE systems is about one $km^2$ [12], the table also shows the approximative area occupation in each case.

| Number of AWES | Nominal power $[MW]$ | Surface area occupied $[km^2]$ |
|---|---|---|
| 2 | 2.2 | 0.125 |
| 4 | 4.4 | 0.25 |
| 6 | 6.6 | 0.375 |
| 8 | 8.8 | 0.5 |
| 10 | 11 | 0.625 |
| 12 | 13.2 | 0.75 |
| 14 | 15.4 | 0.875 |
| 16 | 17.6 | 1 |
| 18 | 19.8 | 1.125 |
| 20 | 22 | 1.25 |
| 22 | 24.2 | 1.375 |
| 24 | 26.4 | 1.5 |
| 26 | 28.6 | 1.625 |
| 28 | 30.8 | 1.75 |
| 30 | 33 | 1.875 |

Table 3.1: Number of AWE systems in the plant and corresponding nominal power.

The study considers an increasing number of AWE systems to investigate the possible advantages of having a large farm. The object is to understand if there's an optimum number of AWE systems (and consequently sizing of other components) from an economical and productive point of view or if increasing the number is always a good choice. The number of AWE systems can be further increased depending on space availability and mutual interference between AWE systems.

### 3.2.2. Electrolyser

The electrolyser is the first element influenced by the farm production. Since one of the final objectives is production maximisation, the electrolyser has to be well-dimensioned to produce as much hydrogen as possible. So, the decision is to dimension the electrolyser first and then deal with the other components. The choices that have been made are such that the residual power (i.e. the power produced by the AWE system less the power used by the electrolyser) is sufficient to supply compressor and water treatment.

The decision on the electrolyser sizes is grounded on the nominal power produced by AWE systems. Ideally, if we want to generate as much hydrogen as possible, we should exploit all the energy for the electrolyser. Hence, the electrolyser dimension should equate to the

AWE systems' nominal power. However, two problems arise:

- The compressor and the water treatment cannot work if all the power is consumed by the electrolyser.
- The wind intensity isn't always over 10 $m/s$, i.e. the minimum value that provides nominal power production. This entails the possibility of investing capital to buy the electrolyser but not exploiting all the capacity. This condition may result in economic inefficiency.

The first issue becomes irrelevant by reserving a part of the power for water treatment and compressor functioning. The electrolyser size is equal to 90% of the AWE system's nominal power, while the other components exploit the remaining 10%.
The second problem is a little bit more complicated. Changing the size highlights a trade-off between costs and hydrogen production. Hydrogen production increases with size, but at the same time, the equipment cost grows. On the other hand, capital expenditure decreases by decreasing the size, but this happens at the expense of hydrogen production.The solution adopted by the study is the following: we take two values of power (73% and 45% of the AWE system's nominal production), assign them to the electrolyser size and then we will evaluate the production and costs in the different cases, taking into account the statistics of wind speed in each one of the considered sites.
In conclusion, we will evaluate three sizes for the electrolyser (90%, 73% and 45%) for each case presented in table 3.1. Such a method permits to identify if it's more advantageous to oversize the electrolyser or to give up on some hydrogen quantity. These results will be presented in section 3.4 and 4.3.

The PEM electrolyser sizes available today are various. The market offers electrolysers ranging from tens of $kW$ to 20-30 $MW$. As can be imagined, employment is different from size to size: the first find use in small industrial applications, while the latter perfectly suit fueling and renewable applications, as in this project. The wide variety of sizes available allows one to find the most suitable solution for each size. Moreover, it's important to underline that the larger electrolysers use modular architectures. Middle-sized electrolysers work parallel to provide the same effect as a hypothetic larger electrolyser. This is a plus in this study since the modular structure ensures the availability of electrolyser dimensions equal (or very similar) to the desired one, as assumed above in section 3.1. Combining different sizes, there will not be problems in matching the requirements.

Concerning the electrolyser consumption, the reference value is 4.5 $kWh/Nm^3$ [20]. Knowing that 1 $Nm^3 = 0.08988$ $kg$ (for hydrogen), the final unitary electrolyzer consumption $E_{EL}$ is around 50 $kWh/kg$. This value is confirmed by the study of Lucas et al. [28].

### 3.2.3. Water treatment

Water treatment is the process necessary for seawater desalination. Thus, the consumption will not be only in terms of energy but also water.
The need for water in hydrogen production oscillates between 10/16 $l/kg_{H_2}$ [17, 32]. Using a conservative estimate, the value considered in this study is 16 $l/kg$.
The water treatment energy consumption $E_{WT}$ is expressed by the following equation:

$$E_{WT} = E_{H_2O} \cdot W_{H_2O} \tag{3.1}$$

where $E_{H_2O}$ is the energy consumed by the water desalination process for each $m^3$ of water and $W_{H_2O}$ is the water consumption in $m^3$ necessary for the production of 1 $kg$ of hydrogen [6]. The reference value for $E_{H_2O}$ is equal to 4 $kWh/m^3_{H_2O}$ [30], while $W_{H_2O} =$ 0,016 $m^3_{H_2O}/kg_{H_2}$ (converted from 16 $l/kg$ expressed before) .

The sizing of the water treatment equipment depends on the maximum water flow needed which in turn depends on the maximum flow of hydrogen generated by the electrolyser. So, before finding the dimension of the water treatment machinery, we need to calculate these two flows. The maximum flow of hydrogen $f_{H_2}$ generated by the electrolyser is equal to:

$$f_{H_2} = \frac{S_{EL}}{E_{EL} \cdot 3600} \tag{3.2}$$

where $S_{EL}$ is the electrolyser size, $E_{EL}$ is the electrolyser unitary consumption and the factor $\frac{1}{3600}$ is need to transform hours into seconds. Once we have $f_{H_2}$, the maximum water flow $f_{H_2O}$ needed is:

$$f_{h_2O} = f_{H_2} \cdot W_{H_2O} \tag{3.3}$$

Now, we can change the measurement unit of $E_{H_2O}$:

$$4kWh/m^3_{H_2O} \rightarrow 14.4 \cdot 10^6 J/m^3_{H_2O} \tag{3.4}$$

In this way, following equation (3.5) we will find the size of water treatment component $S_{WT}$.

$$S_{WT} = \frac{f_{H_2O} \cdot E_{H_2O}}{1000} \tag{3.5}$$

In this equation $E_{H_2O}$ is expressed in $J/m^3_{H_2O}$ and the factor $\frac{1}{1000}$ is needed to transform the water treatment equipment size from $W$ to $kW$.

### 3.2.4. Compressor

The compressor unitary energy consumption $E_{COMP}$ is:

$$E_{COMP} = \frac{n\gamma}{\gamma - 1} \frac{R_{H_2} \cdot T_{IN}}{\eta} \left( \left( \frac{P_{OUT}}{P_{IN}} \right)^{\frac{\gamma-1}{n\gamma}} - 1 \right) \tag{3.6}$$

where $n$ is the number of compression stages, $\gamma$ is the specific heat ratio, $R_{H_2}$ is the ideal gas constant, $T_{IN}$ is the temperature at the compressor inlet, $\eta$ is the compressor efficiency, $P_{OUT}$ is the output pressure and $P_{IN}$ is the input pressure [35, 40]. The value of this parameters are specified in table 3.2.
Since the ideal gas constant is expressed in $J/(kg \cdot K)$, the $E_{COMP}$ is intially in $J/kg$ and converted into $kWh/kg$ multiplying by the conversion factor $2.7777 \cdot 10^{-7}$.

| | Symbol | Value | Measurement unit |
|---|---|---|---|
| **Number of compression stages** | $n$ | 2 | – |
| **Specific heat ratio** | $\gamma$ | 1.4 | – |
| **Ideal gas constant** | $R_{H_2}$ | 4125 | $J/(kg * K)$ |
| **Temperature at compressor inlet** | $T_{IN}$ | 298 | $K$ |
| **Compressor efficiency** | $\eta$ | 0.75 | – |
| **Pressure output** | $P_{OUT}$ | 220 | $bar$ |
| **Ideal gas constant** | $P_{IN}$ | 30 | $bar$ |

Table 3.2: Values needed for compressor energy consumption $E_{COMP}$ [35, 40].

The compressor size $S_{COMP}$ is easily found following a method similar to the one used for water treatment machinery. The dimension depends on the maximum hydrogen flow $f_{H_2}$ provided by the electrolyser. The size is thus expressed by:

$$S_{COMP} = \frac{f_{H_2} \cdot E_{COMP}}{1000} \tag{3.7}$$

where $E_{COMP}$ is expressed in $J/kg$ and the factor $\frac{1}{1000}$ is needed to transform the size from $W$ to $kW$.

### 3.2.5. Hydrogen storage

The storage dimension depends on how much hydrogen we want to stock in the plant. The decision takes into account different criteria as daily hydrogen production and the expected market flow. In addition, we need to remember the assumption seen in section 3.1, stating that hydrogen is picked up by vessels directly from the platform and that the passage of the ships is such that the hydrogen quantity stored in the platform is never greater than the maximum amount produced in a day. Given this consideration, the size of the storage $S_{ST}$ is expressed as:

$$S_{ST} = f_{H_2} \cdot 24 \cdot 3600 \tag{3.8}$$

which provides the dimension expressed in $kg$.

### 3.2.6. BESS

As explained in subsection 2.1.6, the BESS functionality is to provide electricity during the AWE systems' retraction phase in case of problems in AWE systems' self-compensation or generation. It mainly works as a security buffer for AWE systems' correct functioning. Possible issues with self-compensation are much more likely when the number of AWES is small. Indeed, the effects of a system that stops working differ when we have only a couple of units or when the number is about ten. In the first case, having issues with a single AWE system can influence the entire plant's functioning: if we exclude one of the two, the BESS has to provide the energy for the retraction phase. On the other hand, when facing the same situation with 5-10 systems, self-compensation is still guaranteed because the remaining AWE system maintain the average power production.
Besides this consideration, another argument can help us to understand how to size the BESS. As we said, the probability of self-compensation success increases when the number of AWE systems grows. However, also the likelihood of failure rises with the number. The choice is then to divide the dimensioning into three cases, following the criterion:

$$\begin{cases} S_{BESS} = 1\ MW \quad if \quad 0 < n_{AWES} < 11, \\ S_{BESS} = 2\ MW \quad if \quad 10 < n_{AWES} < 21, \\ S_{BESS} = 3\ MW \quad if \quad 20 < n_{AWES} < 31. \end{cases} \tag{3.9}$$

where $S_{BESS}$ is the size of the BESS and $n_{AWES}$ is the number of the AWE systems in the farm.
This operation is comparable to adding an additional, "virtual" AWES every 10 real ones,

generating the nominal power and wholly devoted to supplying the retraction phase of other AWE systems if needed. The correct operation of the system is guaranteed using this sizing, except in case of major failures.

### 3.2.7. Energy consumption for 1 kg of hydrogen

The previous section explained how to size each plant component and the energy consumption required by each activity. It is now possible to conduct a study to understand how the consumption of each piece of equipment impacts the total consumption for producing one kilogram of hydrogen.
The total consumption for the production of one kilogram of hydrogen is equal to 51.18 kWh. Table 3.3 explains how each component affects this value.

| Component | Impact on consumption |
|---|---|
| **Electrolyser** | 97.82% |
| **Compressor** | 2.05% |
| **Water treatment** | 0.13% |

Table 3.3: Impact of each element on the consumption required to produce one kilogram of hydrogen.

As can be seen, electrolysis is unquestionably an energy-intensive procedure. It affects almost 98% of the total value, indicating that the electrolyzer is almost entirely responsible for consumption. Compressor and water treatment make up roughly 2% of the total, making them poorly significant in the overall budget.
Lowering the quantity of energy required will improve the amount of hydrogen generated because hydrogen generation depends on unit consumption as well. Since electrolysis has a major energetic significance, increasing this process's efficiency would make the total process more optimal.

## 3.3. Wind data analysis

Once the unitary energy consumption for each component is computed, wind speed is the only element missing for the hydrogen production evaluation. If the wind intensity over time is known, it's possible to derive the AWE systems's power production and, consequently, the amount of hydrogen generated.

### 3.3.1. Data source and preliminary analysis

For each of the four locations, we need to know the exact values of the wind. These data are obtained from ERA5, a reanalysis of the global climate and weather containing data from 1950 to the present [19]. This study combines models and observations to create a worldwide dataset of a significant number of climate phenomena. Among them, we can also find the intensity of the wind at different altitudes, which is the category of our interest. The data are hourly and gridded into a regular lat-long grid of 0.25 degrees, allowing us to obtain data in the four areas of interest.
For this project, the considered data respect some features:

- The evaluation of wind speed is at 300 meters in height.
- The wind data cover years from 2015 to 2020 and they have an hourly resolution.
- The dataset expresses wind speed using eastern and northern components. Our study needs only the absolute wind speed value, which is calculated taking the vector 2-norm.

Having the data means that this values can be used as input for the AWE system's power curve and that it's possible to find the amount of energy generated. Nevertheless, before executing this operation, the data are analysed to find seasonality trends.

The study assesses the seasonal variation of the data. Analyzing wind intensity values in different periods helps to understand how the power changes during the year. The remarkable aspect of this analysis is not only the fact that permits us to see how the wind phenomena change over the year but also to evaluate the feasibility of a wind farm realization. Indeed, the presence of months with a minor wind intensity (and so production) is part of the normal course of seasons. Despite that, the wind intensity must always be greater than a certain quantity to justify the installation of an offshore plant. A few unproductive days can be justifiable, but whole weeks below the production threshold are a symptom of a not suitable location for this type of RES.
Four weeks are considered to investigate these aspects, each one taken in a different period of the year, each one indicative of a season. In particular: week 5 for winter, week 18 for spring, week 31 for summer, and week 44 for autumn. In addition, the data taken from ERA5 include six years. So, the data that will be compared are the average wind speed for the same week of the six different years.
Figures 3.2, 3.3, 3.4, 3.5 show the seasons comparison in the four sites.

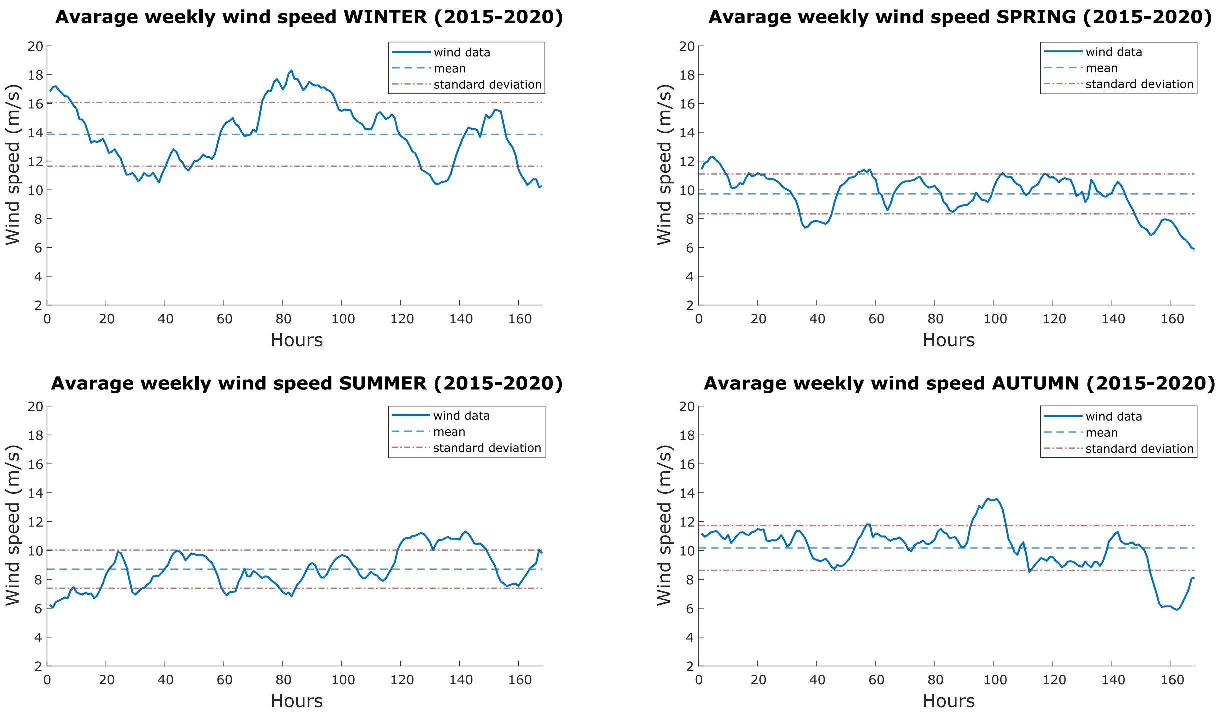



Figure 3.2: Wind seasonal variation in location 1 (Hornsea One).

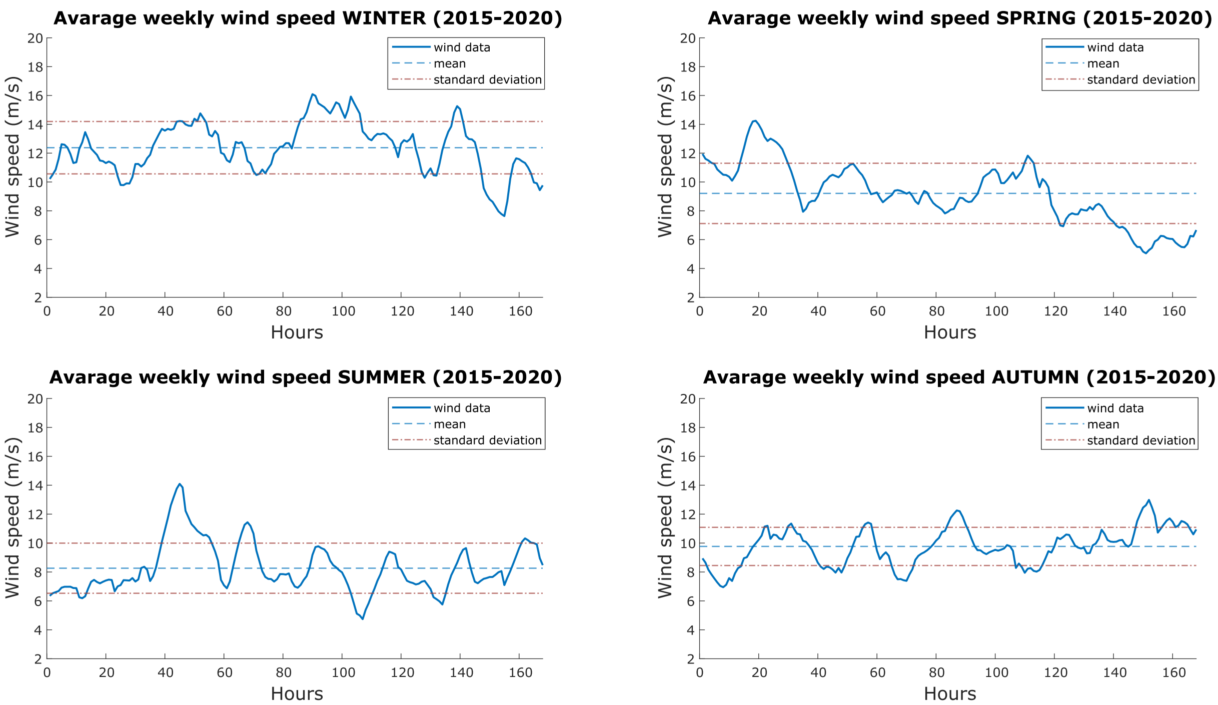



Figure 3.3: Wind seasonal variation in location 2 (Viana do Castelo).

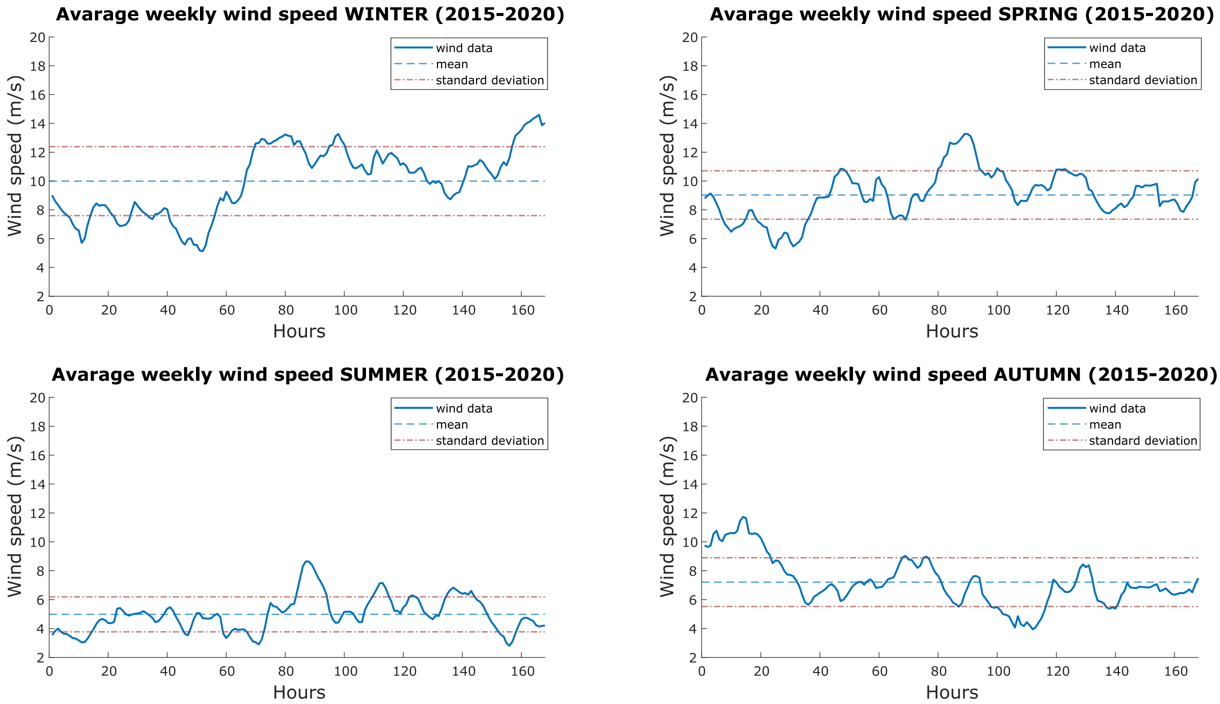



Figure 3.4: Wind seasonal variation in location 1 (Marsala).

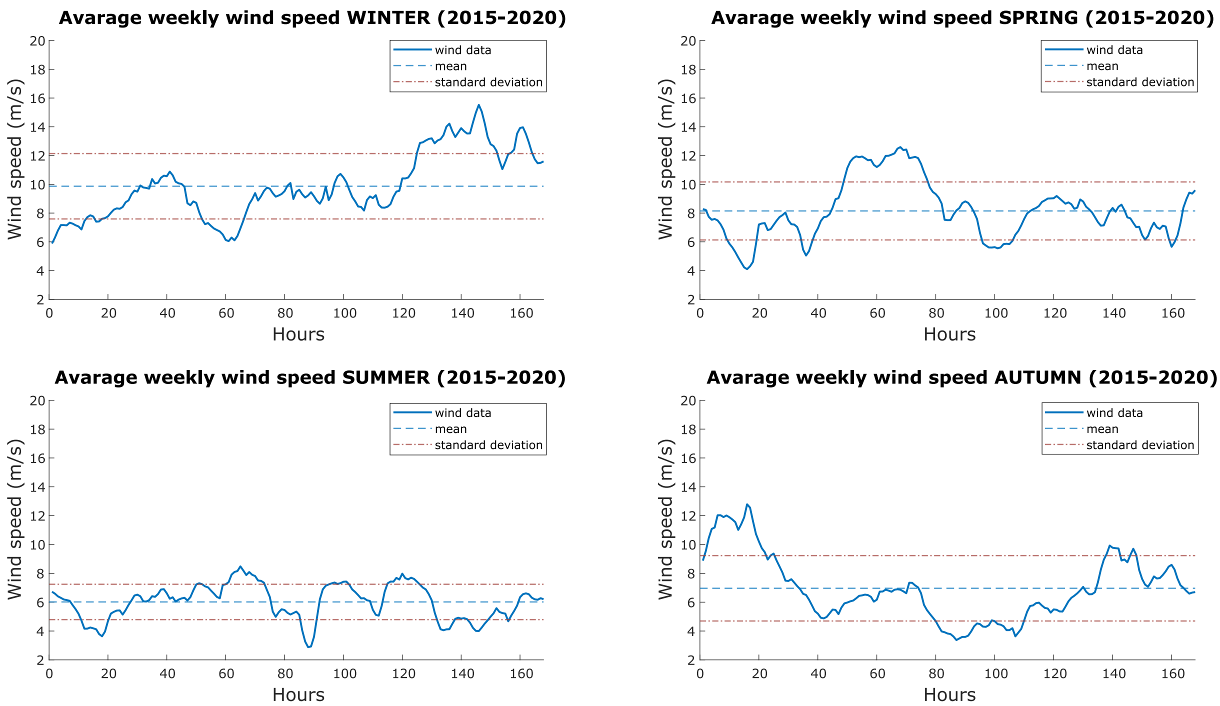



Figure 3.5: Wind seasonal variation in location 1 (Olbia).

The first consideration done looking at the plots concerns the wind speed variation over the year. As expected, there are seasons characterized by more intense winds and seasons

where the winds are weaker. The trend is the same for all four locations: the wind intensity is maximum in winter and minimum in summer, while autumn and spring present intermediate wind speeds, which a range that changes depending on the location, temperatures and weather.
The second aspect considered is the avarage wind speeds in the four sites. These values must be analysed by comparing them with the corresponding energy production of AWE systems. In this case, the situation varies from location to location:

- Hornsea One wind farm never presents values under 5.5 m/s in the periods under investigation, leading us to believe that the AWE systems would be active and productive most of the time. In addition, the speeds are usually greater or equal to 8-10 m/s, meaning that the power production is at the nominal value.
- Viana do Castello is characterised by mean intensity values slightly less than Hornsea One. The conclusions are the same as the previous location.
- The production site of Marsala differs from what we have seen so far. The winter wind speeds are always above the production limit ($> 5$ m/s) and also higher than 8-10 m/s for most of the time. Spring and autumn have winds generally suitable for production (the average varies between 7 and 9 m/s), but here appear some time slots when the AWE systems are unproductive (speed $<5$ m/s). The summer period highlights problems with AWE system' functioning since many values are below 5 m/s. In the reference week, the AWE systems may work only half-time.
- Olbia location has features very similar to Marsala: high/medium productivity in winter, spring and autumn but wind speeds near to lower limit during summer. By the way, this site has fewer unproductive slots during summer reference week than Marsala.

One result of this investigation is the adequacy of the first and second locations for the study purposes, as evidenced by the real presence of wind turbine farms. On the other hand, Marsala and Olbia seem to be less appropriate. Even if the production is satisfactory for most of the year, unproductive days may cause some issues. The quality and the economic viability of these sites will be reevaluated during the cost analysis in section 4.3.

### 3.3.2. Wind probability density function

The power and hydrogen production are not calculated directly using the wind data provided by ERA5. The wind values are first elaborated and used to extrapolate the probability density function for each location. Thus, it will be enough to associate each wind speed value with the corresponding AWE system's power production. Then, combining these power values with the wind speed occurrence probabilities, the expected production over a selected prediction horizon is obtained.

The first operation is the extrapolation of the dataset's maximum and minimum speed intensities. The above numbers are used as the first and last points of a wind speed scale with a 0.5 m/s discretization. This range will be the independent variable of the empirical probability density function. Then, we count how much time each speed value appears in the dataset and we transform it into a likelihood of occurrence. In this way, we have built the probability density function, which associates each value of the independent variable (i.e. wind speed) with the occurrence probability of that event.
This procedure is repeated for each location. Figures 3.6, 3.7, 3.8, and 3.9 show the four probability density distributions that resulted.

Note that the wind probability density function is generally well described by a Weibull distribution with specific shape and scale parameters, which can be estimated using multiple techniques. It's demonstrated that this distribution is an adequate tool for analysing wind speed data. So, if wind data is not completely accessible but the average wind speed is known, Weibull distribution can be used to have a speed distribution with reasonable first-approximation accuracy [33].
In the underlying graphs, the Weibull distribution (with different factor and shape parameters) can be recognised.

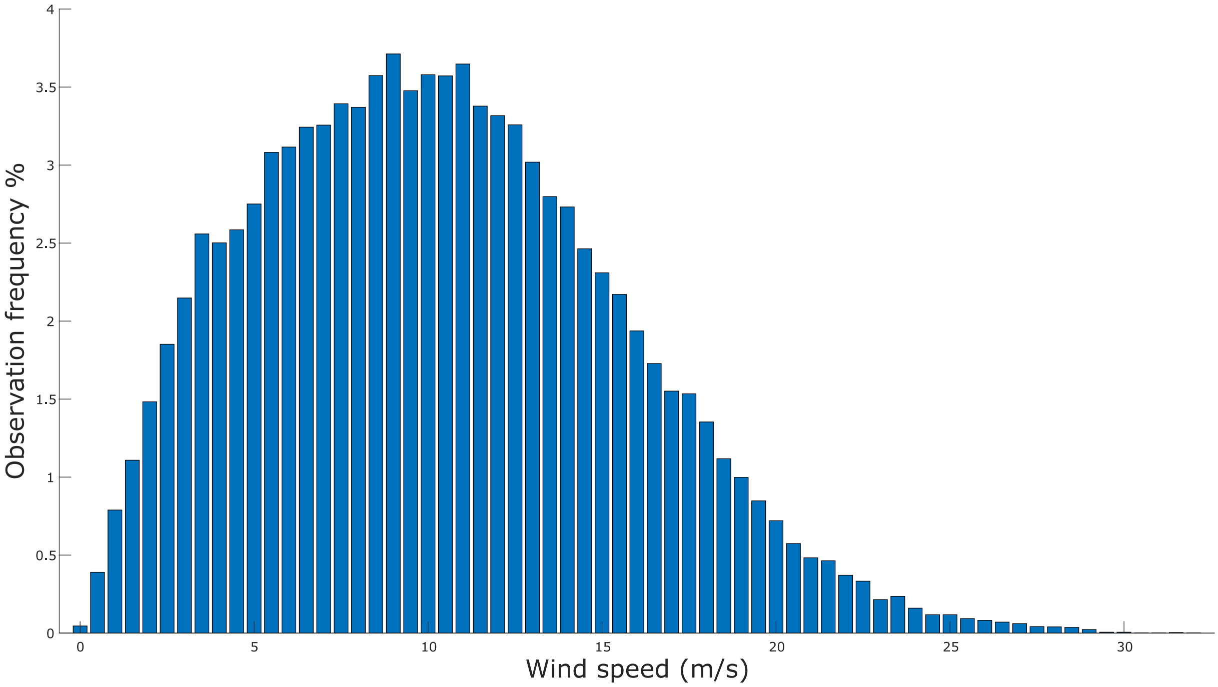



Figure 3.6: Hornsea One's probability density function.

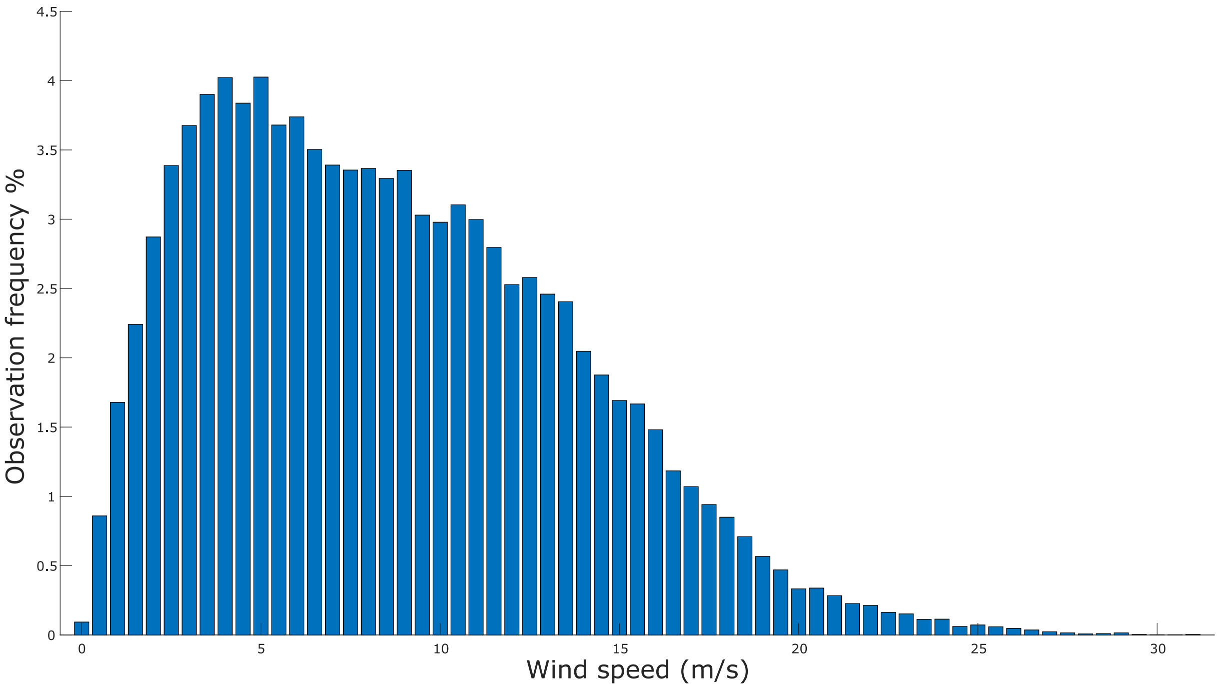



Figure 3.7: Viana do Castello's probability density function.

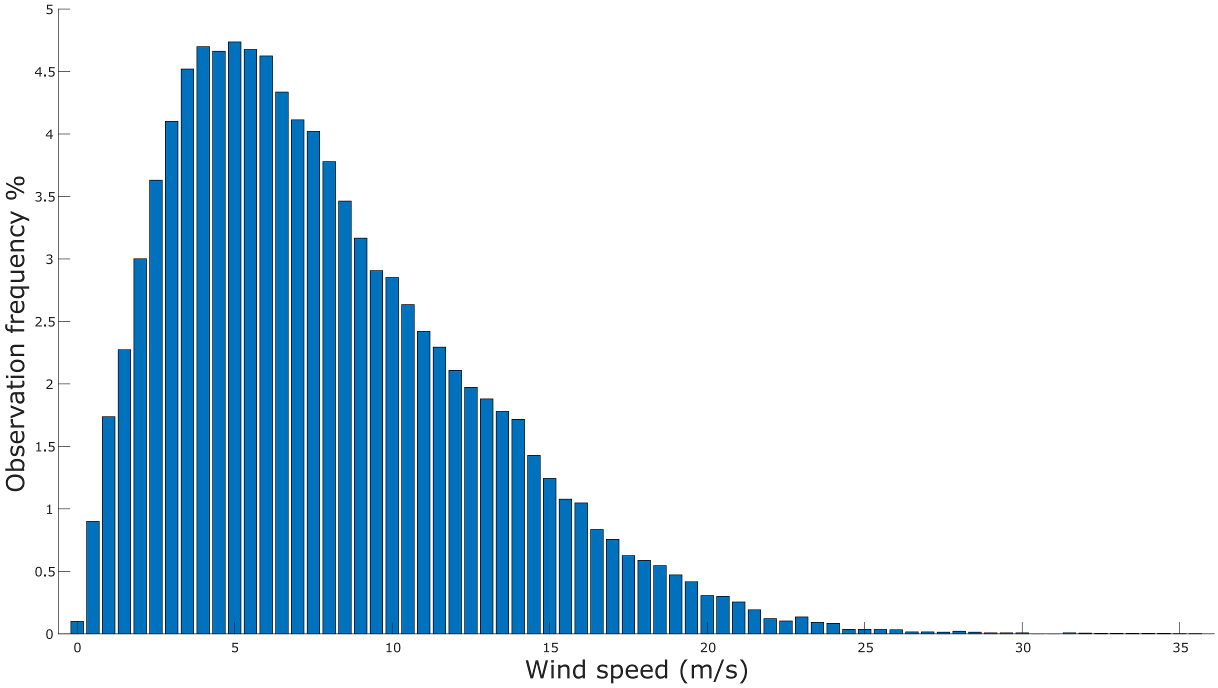



Figure 3.8: Marsala's probability density function.

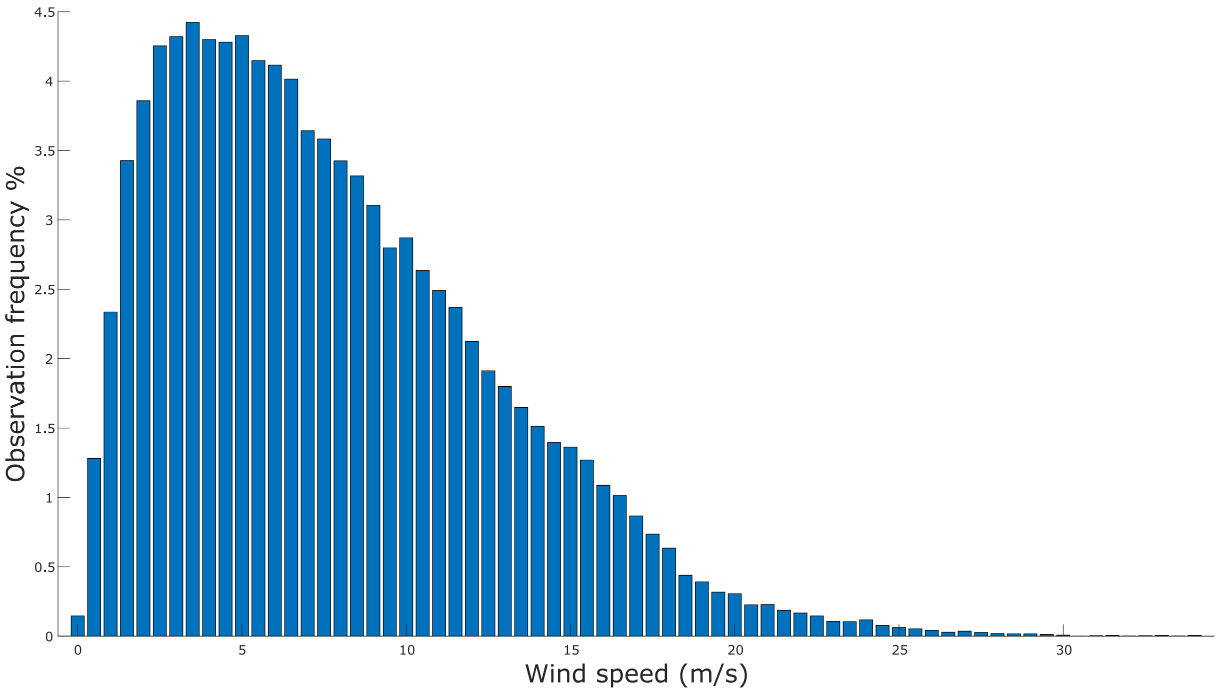



Figure 3.9: Olbia's probability density function.

The speed intensities at the Hornsea One and Viana do Castello sites support the findings of the preliminary analysis. The probabilities are well distributed between the key wind speeds intervals (0-4.5 $m/s$, 5-9 $m/s$, 9.5-25 $m/s$, $>$25 $m/s$), especially for the first location

where the likelihood of a single value is never greater than 2.5%. But more significantly, the values allowing for production are the most likely to occur. However, the second graph's shape is different from the first, and the likelihood of low values increases. On the other hand, Marsala and Olbia's most probable values are shifted to lower speed, meaning that the wind intensities are weaker there.
Table 1 displays the likelihood of occurrence for the various wind speed ranges so that the curves' information may be examined more thoroughly. The four ranges' percentages are acquired, and these values are then split into productive and unproductive categories. In such a way, we can estimate how much time the plant is operating and generating energy for hydrogen production.

| | Wind speed ranges ($m/s$) | | | | Productivity time | |
|---|---|---|---|---|---|---|
| | **0-4.5** | **5-9** | **9.5-25** | **>25** | **Productive** | **Unproductive** |
| **Location 1** | 15.46% | 29.49% | 54.58% | 0.47% | 84.07% | 15.93% |
| **Location 2** | 26.57% | 31.71% | 41.5% | 0.22% | 73.21% | 26.79% |
| **Location 3** | 29.62% | 36.92% | 33.26% | 0.2% | 70.18% | 29.82% |
| **Location 4** | 32.63% | 33.68% | 33.40% | 0.29% | 67.08% | 32.92% |

Table 3.4: Time percentages for different wind intensities. The last two columns show the percentages of time in which the AWE systems are productive or not.

The table emphasizes how the first location is highly preferable to the others.The Hornsea One is 11–17% more productive than the other sites, which corresponds to a remarkable amount of energy and time. When comparing the production of the other three locations, there is only a ±3% variation in the activity time. Nevertheless, location two once more demonstrates that it is more appropriate than the Mediterranean sites. The wind speed ranges show how Viana do Castello works at nominal power for 10% more time than Olbia and Marsala. The last consideration extrapolated from the table is that the unproductivity time mainly depends on the 0-4.5 $m/s$ range, with wind speeds above 25 $m/s$ occurring for very brief periods of time. As a result, it is reasonable to accept the conservative hypothesis of a non-functioning AWE system over 25 $m/s$ suggested in section 3.2.1.

## 3.4. Production analysis

Once we have the components' consumption, the wind data and the probability density function of each location, it's possible to investigate the energy and hydrogen production. The AWE contribution will be studied at first, while the amount of hydrogen produced will be estimated after discussing AWE production.

To estimate the energy produced by the AWES in a year, the first step is to multiply each likelihood times the hours of a year: in this way, we will obtain the yearly number of hours for which a wind speed value occurs. Then, each of these hours is multiplied by the power produced by AWE systems at the corresponding wind intensity. These power levels are obtained using the power curve in figure 3.1. The total energy generated in the year is then determined by summing the individual results of these operations (i.e. all the energies produced).
The results in $GWh$, performed for each location and size of the plant, are displayed in Table 3.5.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 13.84 | 11.39 | 10.28 | 9.99 |
| 4 | 27.68 | 22.78 | 20.56 | 19.98 |
| 6 | 41.53 | 34.16 | 30.84 | 29.97 |
| 8 | 55.36 | 45.55 | 41.12 | 39.96 |
| 10 | 69.21 | 56.94 | 51.40 | 49.95 |
| 12 | 83.05 | 68.33 | 61.68 | 59.95 |
| 14 | 96.89 | 79.72 | 71.96 | 69.94 |
| 16 | 110.74 | 91.11 | 82.24 | 79.93 |
| 18 | 124.58 | 102.49 | 92.51 | 89.92 |
| 20 | 138.42 | 113.88 | 102.79 | 99.90 |
| 22 | 152.26 | 125.27 | 113.07 | 109.90 |
| 24 | 166.10 | 136.66 | 123.35 | 119.89 |
| 26 | 179.94 | 148.05 | 133.63 | 129.88 |
| 28 | 193.79 | 159.43 | 143.91 | 139.87 |
| 30 | 207.63 | 170.82 | 154.19 | 149.86 |

Table 3.5: Annual AWE's production ($GWh$) in each location depending on the plant size.

When looking at table 3.5, two key considerations immediately come to mind. First, individual plant productivity is influenced by the quality of the various sites, as could be expected. The production at Hornsea One is unquestionably the best, followed by Viana do Castello. Olbia and Marsala are less productive, with approximately equal energy values. The second aspect that it's clear in the table is the proportional growth in energy with the increasing number of AWE systems.
Combining these two pieces of information demonstrates how the plant size has an impact on the production disparity between locations. In a real implementation of this study, it is highly likely that the number of AWE systems will not be in the range of a few units but will instead tend to utilize all of the space present in the offshore site, increasing the number of AWE systems. Therefore, location selection becomes much more important than with small plant dimensions.

Besides knowing how much energy the AWE systems farm generates yearly, we're interested in understanding how much hydrogen the plant can produce. This value is one of the most relevant feedback on the plant's performance. Only through the quantity produced can we know what needs we can meet with such a farm.
But first, we need to highlight something before moving on. In the previous chapters, we explained the decision to select different electrolyser sizes to deepen our research. These sizes correspond to 90%, 73%, and 45% of the rated power produced by the AWE system farm. The other components were then sized accordingly. Additionally, we have seen that the electrolyser impacts consumption by 97%, whereas the compressor and water treatment marginally affect them. Given these two factors, it can be claimed that there may be situations where the plant does not employ all the AWE systems production. This phenomenon can happen especially for small electrolyser sizes. In light of this, before moving on is necessary to create a power curve saturated at the maximum power the hydrogen production system can use. First, we must calculate the maximum power $P_{EFF}$ that the system can use. This value is equal to:

$$P_{EFF} = S_{EL} + S_{WT} + S_{COMP} \tag{3.10}$$

The effective power curve is now the AWE system's power curve, saturated at $P_{EFF}$. As a result, all values of the classical power curve that exceed the system's maximum power consumption are transformed to $P_{EFF}$. In this way, the new curve expresses the power utilised when a certain wind intensity occurs. This new power curve might be referred to as the plant's effective power curve.
We can now estimate the energy used by the plant over a year, similarly to how we calculated the energy produced. It is enough to match the power curve and the probability

density function evaluated throughout the year. The output will be the energy used by the plant annually $cons_{TOT}$.
Finally, we can estimate the amount of hydrogen produced in the year. This value derives from the division between the energy used in the year $cons_{TOT}$ and the unitary consumption $E_{TOT}$, as explained by equation 3.11.

$$Q_{H_2} = \frac{cons_{TOT}}{E_{TOT}} \tag{3.11}$$

Obviously, as in the previous cases, the production depends on the sizing of the plant and the location.

In contrast to what happened for the annual AWE production numbers, three tables are used in this case to display the annual hydrogen amount. This is because the study assumes three possible electrolyser sizes, as described in subsection 3.2.2. Table 3.6 considers $S_{EL}$ equal to 45% of AWES's nominal production, table 3.7 $S_{EL}$ equal to 73% of AWES's nominal production and table 3.8 $S_{EL}$ equal to 90% of AWES's nominal production.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 139.86 | 118.46 | 111.01 | 106.78 |
| 4 | 279.72 | 236.92 | 222.02 | 213.57 |
| 6 | 419.58 | 355.38 | 333.03 | 320.35 |
| 8 | 559.19 | 473.49 | 443.62 | 426.76 |
| 10 | 699.05 | 591.95 | 554.63 | 533.55 |
| 12 | 838.91 | 710.41 | 665.64 | 640.33 |
| 14 | 978.49 | 828.54 | 776.25 | 746.76 |
| 16 | 1118.35 | 947.01 | 887.26 | 853.54 |
| 18 | 1258.21 | 1065.46 | 998.27 | 960.33 |
| 20 | 1391.49 | 1178.51 | 1104.36 | 1062.34 |
| 22 | 1531.11 | 1296.62 | 1214.95 | 1168.75 |
| 24 | 1670.96 | 1415.08 | 1325.97 | 1275.53 |
| 26 | 1810.82 | 1533.54 | 1436.97 | 1382.32 |
| 28 | 1950.68 | 1652.01 | 1547.98 | 1489.10 |
| 30 | 2090.54 | 1770.47 | 1658.99 | 1595.89 |

Table 3.6: Annual hydrogen production ($10^3 kg$) when $S_{EL}$ is equal to 45% of $P_{KITE_{NOM}}$.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 214.28 | 178.52 | 164.04 | 158.60 |
| 4 | 428.56 | 357.05 | 328.08 | 317.20 |
| 6 | 642.84 | 535.57 | 492.11 | 475.81 |
| 8 | 857.16 | 714.04 | 656.10 | 634.35 |
| 10 | 1071.16 | 892.26 | 819.76 | 792.60 |
| 12 | 1279.42 | 1064.98 | 979.62 | 947.11 |
| 14 | 1493.43 | 1244.17 | 1143.25 | 1105.35 |
| 16 | 1707.71 | 1422.70 | 1307.29 | 1263.95 |
| 18 | 1921.99 | 1601.22 | 1471.33 | 1422.55 |
| 20 | 2136.27 | 1779.75 | 1635.36 | 1581.16 |
| 22 | 2350.59 | 1958.22 | 1799.35 | 1739.70 |
| 24 | 2564.87 | 2136.74 | 1963.39 | 1898.30 |
| 26 | 2779.15 | 2315.26 | 2127.43 | 2056.90 |
| 28 | 2993.43 | 2493.79 | 2291.46 | 2215.51 |
| 30 | 3207.43 | 2672.01 | 2455.12 | 2373.76 |

Table 3.7: Annual hydrogen production ($10^3 kg$) when $S_{EL}$ is equal to 73% of $P_{KITE_{NOM}}$.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 259.40 | 214.03 | 193.98 | 188.31 |
| 4 | 518.51 | 427.77 | 387.62 | 376.33 |
| 6 | 777.92 | 641.81 | 581.60 | 564.64 |
| 8 | 1037.37 | 855.79 | 775.52 | 752.90 |
| 10 | 1290.77 | 1065.00 | 965.29 | 937.07 |
| 12 | 1549.88 | 127.74 | 1158.91 | 1125.07 |
| 14 | 1809.01 | 1492.45 | 1352.48 | 1313.02 |
| 16 | 2068.12 | 1706.19 | 1546.13 | 1501.04 |
| 18 | 2327.53 | 1920.23 | 1740.11 | 1689.35 |
| 20 | 2589.93 | 2134.26 | 1934.08 | 1877.67 |
| 22 | 2846.08 | 2347.95 | 2127.67 | 2065.62 |
| 24 | 3105.49 | 2561.98 | 2321.65 | 2253.93 |
| 26 | 3364.89 | 2776.02 | 2515.63 | 2442.25 |
| 28 | 3618.58 | 2985.54 | 2705.78 | 2625.77 |
| 30 | 3877.70 | 3199.27 | 2899.37 | 2814.74 |

Table 3.8: Annual hydrogen production ($10^3 kg$) when $S_{EL}$ is equal to 90% of $P_{KITE_{NOM}}$.

The three tables clearly show the same two tendencies found in table 3.5: hydrogen production rises with the number of AWE systems, and Hornsea One farm is the most productive due to unmatched wind speeds. Additionally, it is evident that production rises as the electrolyser gets bigger, which is a natural result of the increased volume of work the component can handle. Although increased output is always a good thing, it does need more investment. Because of the rise in costs, increasing production does not always result in increasing profit. Only through a cost analysis is it feasible to show whether this advantage in terms of quantity produced is economically viable. The chapter 4.3 will present this investigation.

By looking at the tables, one may perform yet another analysis focused on the importance of hydrogen production rates. The question that arises is what kind of needs can satisfy these quantities of hydrogen.
If we focus on the industrial sector, the Roadmap to Flanders [34] report states that the annual hydrogen requirement for a small chemical or other process industry is equal to 179 760 $kg$ (2 000 000 $Nm^3$) while the needs in a large-scale refinery, chemical or process industry site grow to 8 988 000 $kg$ (100 000 000 $Nm^3$). These values can be compared to the hydrogen quantities listed in the tables to see how easily two or four AWE systems can meet the small-scale requirements. On the other hand, the offshore hydrogen production plant has never been able to satisfy the need for a larger plant.
Looking at the mobility sector, the Roadmap to Flanders report [34] considers a 73-ton per-year consumption for a car refuelling station with a daily number of refuelling operations equal to 50 (4 kg for each refuelling operation). This value transforms to 323-ton per year if we consider a bus refuelling station with 25 daily operations. This means that the offshore plant would be able to supply more than 2000 vehicles daily in the most productive cases.
These considerations might suggest that the hydrogen generation plant is characterised by a non-particularly high production. By the way, this conclusion needs to be accompanied by an examination of the technological advancement of the plant. The electrolyser, compressor, and water treatment systems are here designed following current market offerings. However, with the development of a green hydrogen economy, their effectiveness and consumption ought to improve over the future years, particularly for the electrolyser, which has already undergone extensive research to enhance its capabilities. The same reasoning can be made for AWE systems, even if the 1.1 MW size used for this study is already a future projection. This technology is indeed at an RD level, but the possible developments reach 3 MW for single units, resulting in considerable production improvements.Therefore the hydrogen produced quantity adequateness is very dependent

on the future developments of the hydrogen economy. The appeal of the offshore plant will increase if the improvements are substantial.

# 4 | Cost analysis

## 4.1. Working assumption

All of the following working hypotheses hold for this chapter:

- The compressor, water treatment, BESS and storage are reported with current prices.
- The AWE system and the electrolyser present cost projections for 2040.
- The lifetime of the plant is equal to 20 years.

## 4.2. Components cost

The previous chapters are concerned with the structure of the plant, the wind intensity in the different locations and the production quality. However, technical examination alone is insufficient to comprehend the plant's real economic value. Investigating the expenses of each component and the resulting cost of hydrogen is also necessary. This chapter starts by examining the costs associated with the various plant components, accounting for capital expenditures (CAPEX), operating expenditures (OPEX), and potential equipment replacement throughout the plant's lifetime. Then, the costs and production will be combined to get the unitary cost of hydrogen in various regions. The gathered results will then be analyzed to determine the plant's performance.

### 4.2.1. AWE

The AWE system's cost is one of the most important values of this project. The introductory chapter described how the innovative characteristics of this system go beyond its technological elements and may be noticed in the low cost. The main differences between AWE systems and wind turbines lie, in fact, in their different physical structure, which is one of the most significant costs for both technologies. First, unlike wind turbines, AWES don't require as sturdy foundations. Additionally, the latter's structure weighs a lot due to the large tower and rotor. Instead, AWE systems are made of a light material, which results in significantly lower expenses.

Since this technology is still in the R&D stage, establishing the AWE systems' cost is difficult. The white paper "Getting airborne - the need to realise the benefits of airborne wind energy for net zero" by BVG Associates produced the final value that will be applied to our project [7].
The research finds out the levelized cost of energy (LCOE) trends up to 2050, both for AWE and wind turbines. Figure 4.1 shows the two curves. As you can see, the costs of this system will be significantly greater than those of wind turbines when AWE will enter the market in 2025. As the years go on and technology advances, the two systems will achieve similar costs around 2037, opening the door for a trend shift in the following years.

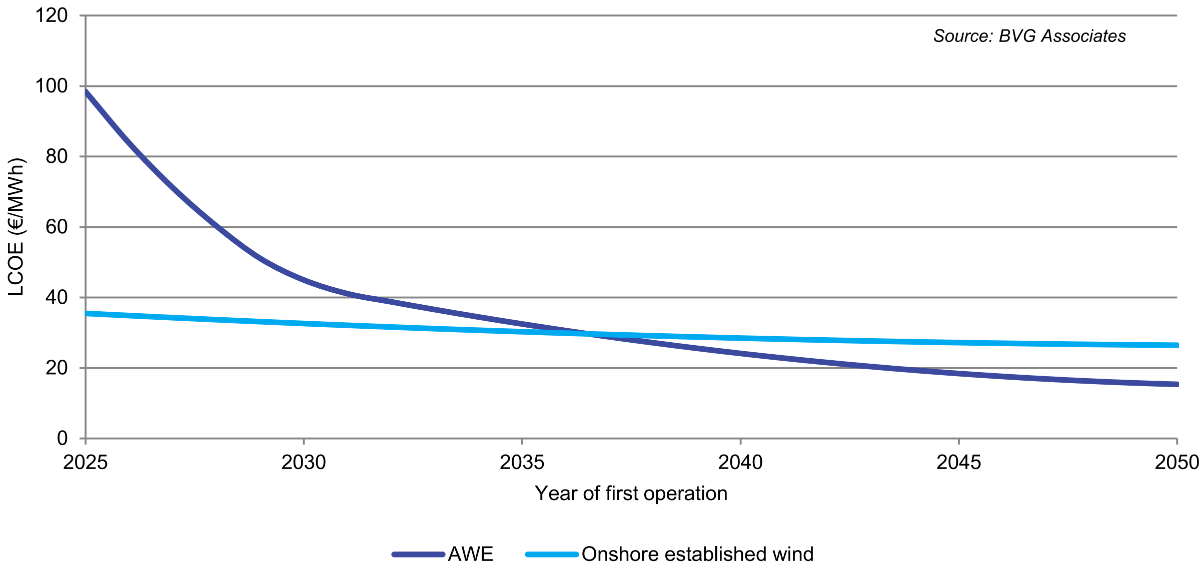



Figure 4.1: Trend in representative LCOE of AWE and established wind turbine technology [7].

This curve was developed based on some knowledge, including learning gains, potential cost savings from AWE, and recent developments in other wind energy sources (i.e. wind turbines). Note that this value includes CAPEX, OPEX, development expenditure (DEVEX) and decommissioning expenditure (DECEX).
The LCOE for our project will be 20 $€/MWh$, which is the projection for 2040-2045. Please note that the main cost difference between an offshore hydrogen production plant with turbines or with an AWE system is directly related to the cost gap between the two

wind technologies. The cost difference between the hydrogen produced by the two various technologies is therefore expected to be approximately comparable to the difference between the costs of AWE and turbines, which translates to a decrease of 30–35% using AWE in 2040. This reduction will rise to 40% till 2050 if the two curves are followed.

### 4.2.2. Electrolyser

Together with AWE, the cost of the electrolyser has a significant impact on the study. The issue is that it's challenging to find the costs (both capital and operational) for this component. It was then decided to estimate this amount, in line with the work done in the "Hydrogen production from the WindFloat Atlantic offshore wind farm" article [28] and based on information from the Roadmap to Flanders research [34].
Cost estimates for PEM electrolysers with MW and multi-MW scale are given in the Roadmap to Flanders. The assumption is that as electrolyser size increases, pricing decreases linearly till reaching the multi-MW scale. For greater values, we conservatively assume the price constant since the literature lacks data for these dimensions, even if the prices are expected to decrease also when the size overcomes the 10 MW. This procedure hold for both CAPEX and OPEX.
Furthermore, Roadmap to Flanders offers cost estimates for 2015, 2030, and 2050. Given that the cost of AWE has been estimated at 2040, it is appropriate to maintain this time horizon also for the electrolyser. To obtain this result, the values of these years are interpolated. Figure 4.2 presents the findings.

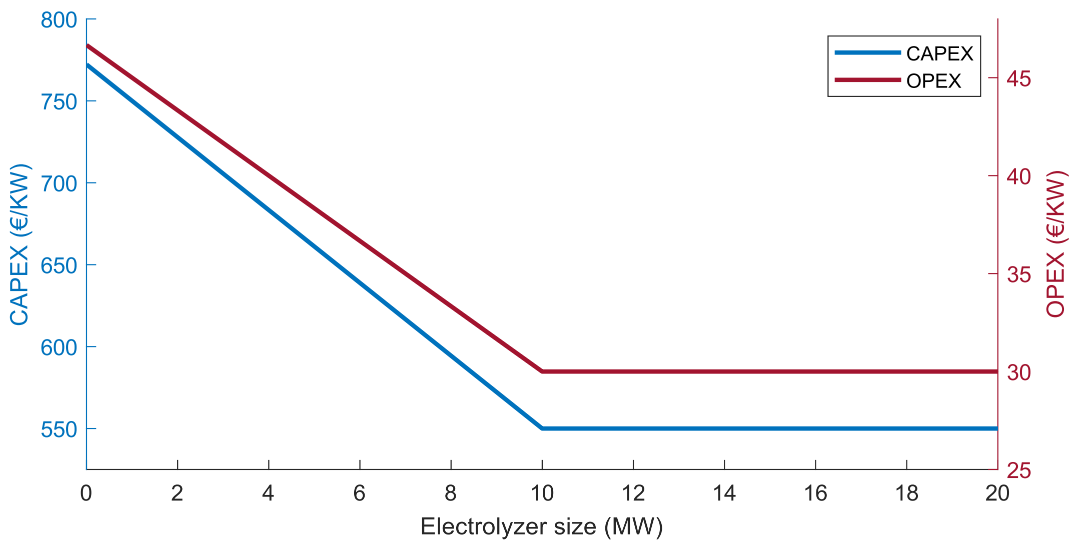



Figure 4.2: CAPEX and OPEX for different sizes of PEM electrolyzer.

Given what has been presented so far, the prices will vary based on the size of the plant. The right values will derive from curve 4.2, depending on the electrolyser dimension. Note that the curve indicates the cost in €/kWh. Then the total CAPEX and OPEX of the electrolyser ($CAPEX_{EL}$ and $OPEX_{EL}$) are obtained by multiplying the size $S_{EL}$ by the value from the graph.

In addition to CAPEX and OPEX, the final cost may be impacted by possible component replacements in the electrolyser. The lifespan of the electrolyser stack is indeed approximately 55000 hours (almost equivalent to 6 years). Therefore, this component will be replaced at least three times throughout the 20-year expected lifetime of the entire plant. The replacement cost (i.e. stack's price) is equal to 40% or 50% of the total electrolyser cost, depending on the dimension of the component (respectively MW or multi-MW scale). This value will thus contribute to the final balance of the electrolyser's expenditures.

The final electrolyser cost $C_{EL}$ is then:

$$C_{EL} = CAPEX_{EL} + OPEX_{EL} \cdot 20 + 3 \cdot C_{STACK} \tag{4.1}$$

where $CAPEX_{EL}$ and $OPEX_{EL}$ are the CAPEX and the OPEX for a specific size of electrolyser and $C_{STACK}$ is the cost of the stack replacement. Note that the OPEX is multiplied by 20 since it's a yearly cost and the plant lifetime is 20 years.

### 4.2.3. Water treatment

As explained in section 2.1.3, the water treatment component takes care of the seawater desalination, which is essential for the subsequent electrolysis process. By the way, there isn't enough research on this topic and most of it isn't very focused on the economic aspect of employing SWRO for hydrogen production. Thus, the costs considered here come from SWRO studies for different purposes.

The CAPEX reference value for the process is equal to 1313 $\frac{\$}{m^3/day}$ [2] (equal to 1313 $\frac{€}{m^3/day}$, considering the actual unitary euro-dollar exchange rate). But this number expresses a unitary cost and not the entire one. To obtain the final value $CAPEX_{WT}$, we need to multiply it by the maximum water flow $f_{H20}$ achievable by the machinery, expressed in $m^3/day$. The OPEX is estimated to be equal to 6% of the CAPEX, as it happens for the electrolyser.

The final cost of the water treatment $C_{WT}$ is thus:

$$C_{WT} = CAPEX_{WT} + OPEX_{WT} \cdot 20 \tag{4.2}$$

where $CAPEX_{EL}$ and $OPEX_{EL}$ are the CAPEX and the OPEX for the water treatment.

As AWES and electrolysers, the price of the SWRO equipment is strictly dependent on the development and the spread of this technology. Since desalination is a procedure that will be utilized more frequently in the future and new desalination techniques are being developed, it's feasible that less expensive and more effective technologies will exist.

### 4.2.4. Compressor

The compressor is the plant component most widespread in industry. Nevertheless, a proper estimate of the costs it's hard to find. The price can range from 144 €/kW to 18,500 €/kW, according to the analysis of the "D8.3 Report on the costs related with PtG technologies and their potentials across the EU." [35].
The formula here employed for the CAPEX computation is:

$$CAPEX_{COMP} = 15000 \cdot \left( \frac{S_{COMP}}{10kW} \right)^{0.9} \tag{4.3}$$

where $S_{COMP}$ is the size of the compressor [35]. Equation (4.3) was chosen because it follows a similar logic to that used for the electrolyser, accounting for potential cost reductions at increasing scale. In this case, the OPEX represents 3% of the capital expenditures.

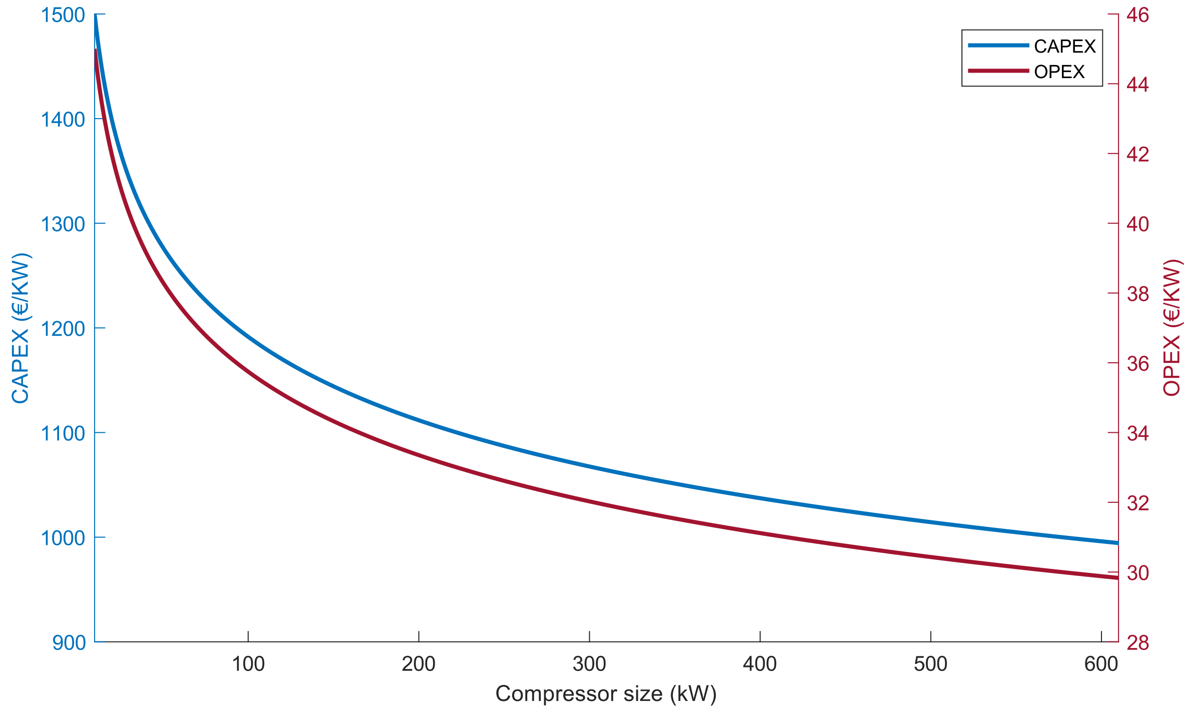



Figure 4.3: CAPEX and OPEX for different sizes of compressor.

Figure 4.3 displays the pricing trends. By the way, keep in mind that the CAPEX equation is a general estimation which could become less effective by changing some process parameters.

The compressor lifetime requires an additional consideration. This component's lifespan is typically ten years. This suggests that the compressor needs to be changed at least once over the time horizon.

The final cost of the compressor $C_{COMP}$ is:

$$C_{COMP} = 2 \cdot (CAPEX_{COMP} + OPEX_{COMP} \cdot 10) \tag{4.4}$$

where $CAPEX_{COMP}$ and $OPEX_{COMP}$ are the CAPEX and the OPEX for the compressor. They are both multiplied by two, since there's the need of one replacement during the 20 years.

### 4.2.5. Storage

The price for the storage is simply extracted from the Roadmap to Flanders [34]. The unitary cost is equal to 225 €$/kg$, considering storage at 200/220 bar as considered in our study. The storage dimension is equal to the maximum amount of hydrogen generated in a day, as explained in 3.1. Then, the cost of the storage $C_{ST}$ is:

$$C_{ST} = 225 \, \frac{€}{kg} \cdot S_{ST} \tag{4.5}$$

where $S_{ST}$ is the size of the storage.

Note that there's no OPEX for the storage since we expect to have no expenditure in managing it. So, the cost is only composed of the CAPEX.

### 4.2.6. BESS

Prices for the BESS vary depending on the size and kind of battery selected. In accordance with the dimension of the other plant components, we chose three BESS capacities: 1 MW, 2 MW, or 3 MW, as illustrated in chapter 3.2.6. However, the identification of the time window in which this power will be provided is also necessary for accurate cost calculation. This project considers one-hour systems (1 MW/1 MWh battery and so on), which are sufficient to supply AWES in emergency situations.

The expenses for the BESS systems utilized in this project were determined using data supplied by a supplier, which are illustrated in table 4.1.

| | Hours | $\frac{€}{kW}$ | $\frac{€}{kWh}$ |
|---|---|---|---|
| **Commercial BESS (150 kW/300 kWh)** | - | 2510 | 944 |
| **Utility scale BESS (5 ÷ 50 MW)** | 1 | 813 | 813 |
| | 2 | 1136 | 568 |
| | 4 | 1756 | 439 |
| | 6 | 2370 | 139 |
| **Utility scale BESS (> 50 MW)** | 1 | 604 | 604 |
| | 2 | 864 | 432 |
| | 4 | 1413 | 353 |
| | 6 | 1961 | 327 |

Table 4.1: BESS costs.

Once we have the value in table 4.1, the data are interpolated to find the prices for the desired BESS sizes. The cost of the battery $C_{BESS}$ is then 2212587 for 1 $MW$, 3725381 for 2 $MW$ and 4538381 for 3 $MW$.

Be aware that the costs listed above include the cost of BESS equipment as well as project planning and installation. For the battery, there is no consideration of OPEX.

### 4.2.7. Plant total cost

In the previous sections, we only discussed expenses in terms of formulas. The following table provides a more thorough breakdown of the expenditures for the Hornsea One plant using 30 AWES and 90% of the farm's nominal production. With this information, it is possible to see the orders of magnitude of the expenses to support, providing a more realistic and concrete vision than that supplied until now.

| | Cost (M€) |
|---|---|
| **AWES** | 79.38 |
| **Electrolyser** | 59.25 |
| **Water treatment** | 0.66 |
| **Compressor** | 1.52 |
| **Storage** | 3.23 |
| **BESS** | 4.54 |
| **Total costs** | 148.58 |

Table 4.2: Costs for Hornsea One plant using 30 AWES and sizing the electrolyser at 90% of the farm's nominal production.

## 4.3. Hydrogen unitary cost

Thanks to the cost analysis carried out in section 4.2, we may obtain a preliminary understanding of the plant's costs and their potential impact on the final price of hydrogen. However, this first inspection only provides a broad and approximative picture. In this section, we will elaborate on the costs already identified to determine the total cost of the plant and the final unitary cost of hydrogen in different situations (sizes and locations).

### 4.3.1. Computation

The first consideration is to divide the cost of AWE systems from the ones of the other components of the system. In fact, the AWES' expenditures are expressed as LCOE rather than component pricing. As a result, the cost of this component will be determined by how much electricity the plant uses. Conversely, the electrolyser, water treatment system, compressor, storage and BESS have a fixed cost, which was previously illustrated.
To calculate the entire cost of the energy supplied to the plant, it's necessary to asses the total consumption of the components. The amount of energy required to produce 1 kilogram of hydrogen $E_{TOT}$ was found out in equation (3.10). The annual energy requirements $cons_{TOT}$ of the plant are then:

$$cons_{\ TOT} = E_{TOT} \cdot Q_{H_2} \tag{4.6}$$

where $E_{TOT}$ is the total unitary energy consumption $kWh/kg$ for 1 kg of hydrogen and $Q_{H_2}$ is the hydrogen production in one year in $kg$. The final cost for the energy consumed $C_{ENERGY}$, which is equivalent to the cost due to the AWES' CAPEX, OPEX, DEVEX and DECEX, is thus:

$$C_{ENERGY} = LCOE \cdot cons\ _{TOT} \tag{4.7}$$

where LCOE is the levelized cost of energy equal to 20 €$/MWh$ and $cons\ _{TOT}$ is the total consumption of energy expressed in $MWh$.
Once this has been done, it's possible to evaluate the fixed cost provided by the other components. The total amount of fixed cost $C_{FIXED}$ is given by:

$$C_{FIXED} = C_{EL} + C_{WT} + C_{COMP} + C_{BESS} + C_{ST} \tag{4.8}$$

where $C_{EL}$ is the electrolyser cost, $C_{WT}$ is the water treatment equipment cost, $C_{COMP}$ is the compressor cost, $C_{BESS}$ is the battery energy storage system cost and $C_{ST}$ is the storage cost.
The total amount of expenditures in the plant lifetime is then:

$$C_{TOT} = C_{FIXED} + 20 \cdot C_{ENERGY} \tag{4.9}$$

since the cost of the energy $C_{ENERGY}$ is annual and needs to be multiplied by the 20-years lifetime while $C_{FIXED}$ is already evaluated along this time horizon.

The just-explained approach determines the cost of the plant over 20 years. This value can give an idea of the expenditure's order of magnitude for the plant, which helps in understanding the possible investments in a similar project. The entire cost, however, makes it complicated to figure out how the expenditures are distributed across production and what is the unitary cost of generating hydrogen $C_{H_2}$. To obtain this last value, as shown by equation (4.10), it is sufficient to divide the entire cost $C_{TOT}$ by the total amount of hydrogen produced yearly $Q_{H_2}$, multiplied by 20.

$$C_{H_2} = \frac{C_{TOT}}{Q_{H_2} \cdot 20} \tag{4.10}$$

The unitary hydrogen cost is the easiest and better way to assess a plant's economic quality. It is the selling price at which the investment can be recovered over the lifetime. Therefore, it also serves as the starting point for the selling price on the market. All the supplier's profit will be the difference between this value and the ultimate selling price. It is crucial to keep the unitary cost of hydrogen as low as possible to enhance profits and make the hydrogen economy more widely accessible.

### 4.3.2. Analysis of unitary cost in the different locations

The following tables present the results for the unitary hydrogen cost for each of the project sizing conditions. More precisely, Table 4.3 considers $S_{EL}$ equal to 45% of AWE systems's nominal production, table 4.4 $S_{EL}$ equal to 73% of AWE systems's nominal production and table 4.5 $S_{EL}$ equal to 90% of AWE systems's nominal production.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 2.88 | 3.21 | 3.36 | 3.45 |
| 4 | 2.45 | 2.71 | 2.82 | 2.89 |
| 6 | 2.29 | 2.51 | 2.61 | 2.68 |
| 8 | 2.19 | 2.40 | 2.49 | 2.55 |
| 10 | 2.12 | 2.31 | 2.40 | 2.45 |
| 12 | 2.15 | 2.35 | 2.44 | 2.50 |
| 14 | 2.09 | 2.28 | 2.36 | 2.41 |
| 16 | 2.03 | 2.21 | 2.29 | 2.34 |
| 18 | 1.98 | 2.15 | 2.22 | 2.27 |
| 20 | 1.94 | 2.10 | 2.17 | 2.22 |
| 22 | 1.95 | 2.12 | 2.19 | 2.24 |
| 24 | 1.94 | 2.10 | 2.17 | 2.21 |
| 26 | 1.93 | 2.09 | 2.16 | 2.20 |
| 28 | 1.92 | 2.08 | 2.15 | 2.19 |
| 30 | 1.91 | 2.07 | 2.14 | 2.18 |

Table 4.3: Hydrogen production cost (€/$kg$) when $S_{EL}$ is equal to 45% of $P_{KITE_{NOM}}$.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 2.63 | 2.95 | 3.12 | 3.19 |
| 4 | 2.32 | 2.58 | 2.71 | 2.77 |
| 6 | 2.18 | 2.41 | 2.53 | 2.58 |
| 8 | 2.08 | 2.29 | 2.40 | 2.45 |
| 10 | 2.00 | 2.20 | 2.30 | 2.34 |
| 12 | 1.99 | 2.19 | 2.29 | 2.33 |
| 14 | 1.96 | 2.15 | 2.25 | 2.29 |
| 16 | 1.94 | 2.13 | 2.22 | 2.26 |
| 18 | 1.93 | 2.11 | 2.21 | 2.25 |
| 20 | 1.91 | 2.09 | 2.19 | 2.23 |
| 22 | 1.93 | 2.10 | 2.21 | 2.25 |
| 24 | 1.92 | 2.10 | 2.19 | 2.23 |
| 26 | 1.91 | 2.09 | 2.19 | 2.22 |
| 28 | 1.91 | 2.08 | 2.18 | 2.22 |
| 30 | 1.90 | 2.08 | 2.17 | 2.21 |

Table 4.4: Hydrogen production cost (€$/kg$) when $S_{EL}$ is equal to 73% of $P_{KITE_{NOM}}$.

| AWES' number | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| 2 | 2.56 | 2.89 | 3.08 | 3.14 |
| 4 | 2.28 | 2.54 | 2.70 | 2.75 |
| 6 | 2.14 | 2.37 | 2.51 | 2.56 |
| 8 | 1.96 | 2.16 | 2.28 | 2.32 |
| 10 | 1.95 | 2.14 | 2.26 | 2.29 |
| 12 | 1.98 | 2.18 | 2.30 | 2.34 |
| 14 | 1.96 | 2.16 | 2.28 | 2.32 |
| 16 | 1.95 | 2.15 | 2.26 | 2.30 |
| 18 | 1.94 | 2.13 | 2.25 | 2.28 |
| 20 | 1.93 | 2.12 | 2.24 | 2.27 |
| 22 | 1.94 | 2.13 | 2.25 | 2.28 |
| 24 | 1.93 | 2.12 | 2.24 | 2.27 |
| 26 | 1.92 | 2.12 | 2.23 | 2.26 |
| 28 | 1.92 | 2.11 | 2.22 | 2.26 |
| 30 | 1.92 | 2.10 | 2.22 | 2.25 |

Table 4.5: Hydrogen production cost (€$/kg$) when $S_{EL}$ is equal to 90% of $P_{KITE_{NOM}}$.

The first thing that becomes evident when comparing tables 4.3, 4.4, and 4.4 is, once again, how better the Hornsea One farm is than the others.
In the worst situation (locations 1 and 4), the difference between the sites can approach 0.60 euros per kilogram, nearly 18-20% of the overall unitary cost. Even if the difference in €/kg changes, note that the percentage difference between the two sites remains relatively constant for all plant sizes (± 3/4% depending on the electrolyser dimensioning). In other words, at the same production expenditure, we will have 5 kg of hydrogen in the Hornsea One farm and around 4 kg in the Taormina plant. In this example, it might just seem like a tiny difference. However, the discrepancy significantly grows if we transpose these numbers on a broad scale. For example, if we take a middle-sized plant with 16 AWE systems and an electrolyser's size that is 90% of the AWE systems' nominal power, the production costs for location 1 are 1.95 €/kg and for location 4 are 2.30 €/kg. Considering 1500 t of hydrogen (corresponding to the annual production for Marsala farm), the production costs are respectively 2 925 000 € and 3 450 000 €. The difference, 525 000 €, is a considerable amount.
Looking at the other sites, we can see how expenses correspond to the section 3.4 analysis. The second-best production location is Viana do Castello, while the Mediterranean farms are about equivalent in their performances. In any scenario, the cost differential from the Hornsea One farm never drops below 0.15 €/kg.

The second conclusion from the data in the tables concerns the three probable sizes of electrolyser. The study in subchapter 3.4 highlighted a production increase when the electrolyser's dimension grows. Since the production costs are inversely proportional to the amount of hydrogen, this trend is expected to invert in tables 4.3, 4.4 and 4.5. As a result, when the power of the electrolyser increases, the unitary cost of hydrogen should be lower. By the way, increasing the electrolyser dimension not only means rising production but also making a significant investment in this equipment. This expenditure may not be compensated by higher hydrogen output.
Observing the tables, it is possible to conclude that the anticipated tendency finds confirmation when employing a small number of AWES $n_{KITE}$ (10-12 AWE systems). When $n_{KITE}$ increases, we can observe that the unitary cost for different electrolysers' sizes tends to settle down or to increase by a maximum of 1-5 cents/kg. As previously stated, this is a problem of non-compensation between the expenditures and the production's increment.
In light of this, we might conclude that, depending on the location and operating conditions, it is not always good to expand the size of the electrolyser (with an equal number of AWE systems) unless the rated power of each AWES unit is increased as well. However,

it is always important to consider how much more hydrogen is produced. As a result, it is feasible to state that no circumstance is always preferable to another, but the sizes must be adjusted by analysing the case study. For example, the price difference between the first and the third table for a farm of 30 AWES in location 1 is 0.01 €/kg. The production differential is almost 1700 tons more hydrogen, though. Therefore, it is feasible to think that in a case as extreme as this one, the productive advantage can compensate for the slight rise in the base cost.

It's possible to identify another trend by looking at the tables. In general, when the number of AWES increases, the unitary cost of hydrogen declines. This evolution seems reasonable, given that producing more hydrogen enables a better amortisation of costs. We can observe, however, that the unit cost rises by a few cents per kilogram every time we go from 10 to 12 AWE systems and from 20 to 22 AWES. The only exception to this phenomenon is between 10 and 12 AWE systems, with the electrolyser dimensioned at 73% of the AWES' nominal power. Even in this instance, though, we observe that the price drop is only 0.01 euros per kilogram, less than the most notable drops in the neighbouring sizes.
The cause of this phenomenon can be identified in the BESS. This slight cost increase occurs exactly in the intervals where the size of the battery storage changes (from 1 to 2 MW and from 2 to 3 MW). Since such systems have a high price, it is plausible that an increase in production of a single size could not be sufficient to offset the cost rise.

All the considerations that have been carried out so far are significant regarding the individual factors that affect the unit cost of hydrogen, i.e. plant sizing, components' expenditures and locations. However, the most meaningful information that the unit cost can provide us is about the economic competitiveness of the hydrogen produced on our farm. We will then compare the cost per kilogram in tables 4.3, 4.4 and 4.5 and the expected value of levelized cost of hydrogen (LCOH) for the future. Note that the LCOH is the cost estimate per unit of hydrogen needed if one wants to meet the expenses of constructing and running a plant over the plant's lifetime.
Today, the LCOH from renewable resources is approximately 5 €/kg. The range varies depending on the production site and employed RES. Nevertheless, the forecast is that the cost of green hydrogen will considerably decline over the next 30 years. According to the Irena research "Global hydrogen trade to meet the 1.5°C climate goal: Part III - Green hydrogen cost and potential" [24], the LCOH in the regions of our interest will be between 1 and 1.5 €/kg in 2050. Contrary to our work, the IRENA's analysis does not consider the desalination process and the storage costs. Even though these expenses only have a small impact on the unitary hydrogen cost (see section 4.3.3), it is wise to account

for this difference for the future evaluation of the performances. Another analysis from PWC [26] shows slightly greater expenses, with a maximum of 2 €/kg for Europe, due to the limited availability of RES with respect to other world areas.
Given the data collected from [24] and [26], it is possible to compare these costs with the results of tables 4.3, 4.4 and 4.5. The cost values connected to small plant sizes (<12 AWE systems) deviate the most from forecasts, whatever the location under consideration. The numbers in this scenario are more than 2 €/kg, reaching costs of 3.50 €/kg in the case of Marsala, the less profitable area. By increasing the number of AWE systems, costs decrease until values in the range of 1.90-2.18 €/kg when $n_{KITE}$ is maximum, depending on the production site. Note that this is also the most reasonable cost because, when building such a plant, the attempt is to maximise production by installing as many AWES as possible. Though not significantly different, these costs are greater than the forecasts. However, we need to take into account some factors before making conclusions:

- The LCOH prediction doesn't account for desalination and storage as we did.
- The electrolyser's and AWES' expenditures are projections for 2040, not 2050, as in the articles. A ten-year difference can significantly alter such numbers.
- The compressor, water treatment and BESS costs are actual and not future projections. Their price in 2050 can be lower if the hydrogen economy rises and R&D improve these technologies.
- The electrolyser is a component still under development. The possibility of increasing its efficiency from the existing 75–80% to levels of 90–98% is the subject of investigations. An increase in production and a subsequent drop in unit cost would be made possible by this improvement.

All of these factors result in lower plant expenses. Therefore, it is conceivable to think about a possible decrease in unit cost compared to what was discovered using the present assumptions. In this case, prices would thus be close to those predicted by the other studies.

### 4.3.3. Hydrogen unitary cost breakdown

Up to this point, we have looked into the numerous trends of hydrogen unitary cost, highlighting how these cost changes relate to the plant's size. By the way, it is possible to conduct another analysis to make the cost assessment more thorough. Such investigation aims to comprehend the percentages by which our expenses affect the hydrogen cost per kilogram. Knowing how each component influences this value helps to understand which path to follow in the base cost reduction.

The plant's dimensions (AWE systems and electrolyser) are a central factor in determining the base cost composition. The cost of each component can vary significantly based on these sizes and thus its influence on unitary cost. Since the plant can present several combinations for dimensioning, three case studies are employed here to evaluate the general trend. We will now consider 4, 16 and 30 AWES options, all with the three possible choices for the electrolyser. Figure 4.4, 4.5 and 4.6 the pie chart for the cost breakdown for these three options. Note that every figure includes three graphs, one for each electrolyser dimension: respectively, 45%, 73% and 90% of the AWE systems' nominal power.

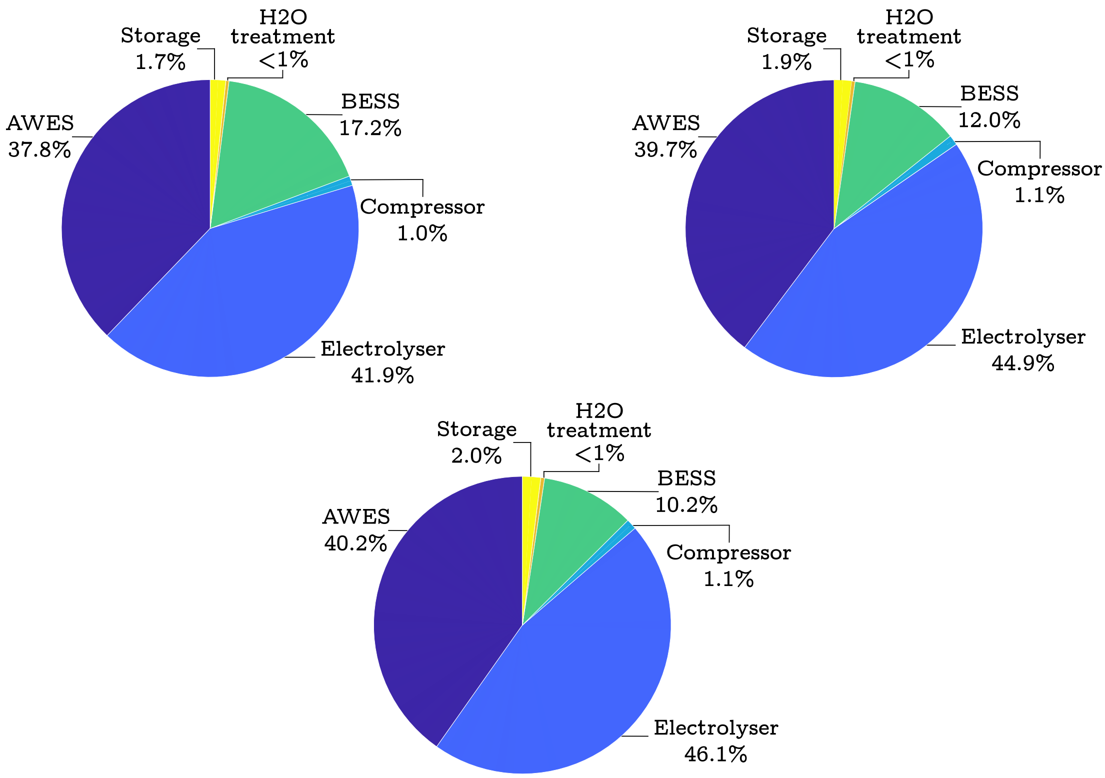



Figure 4.4: Unitary cost analysis when the farm is composed by 4 AWES.

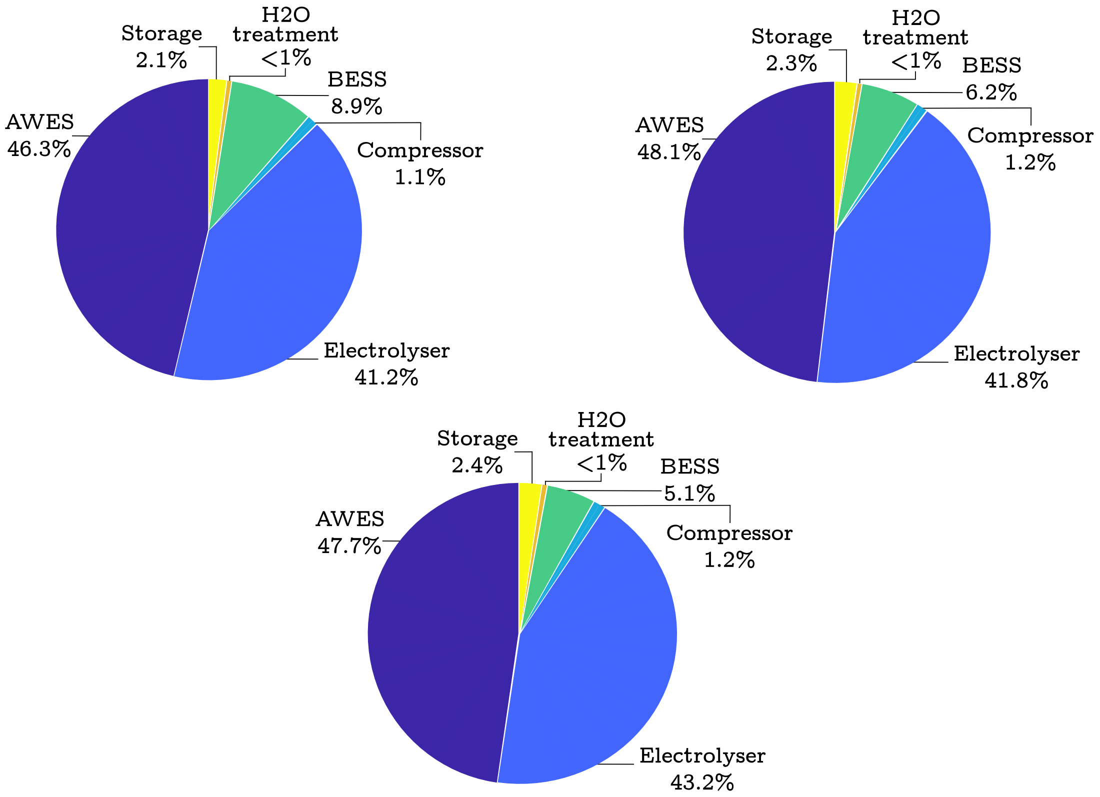



Figure 4.5: Unitary cost analysis when the farm is composed by 16 AWES.

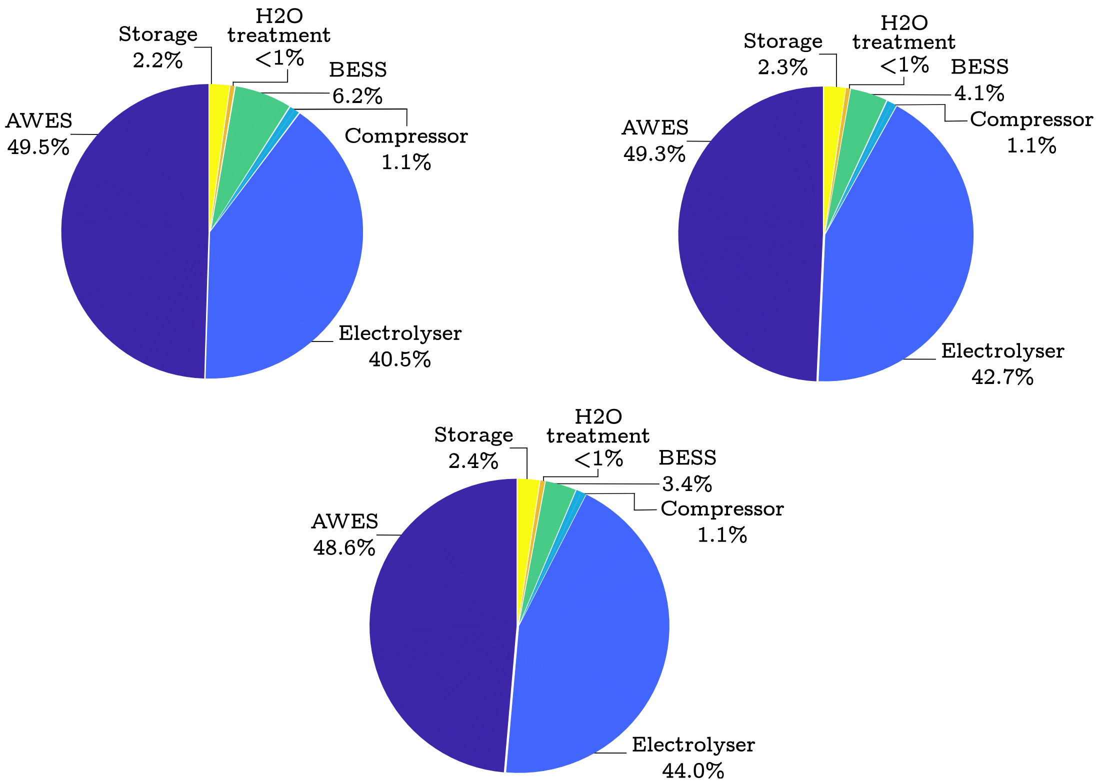



Figure 4.6: Unitary cost analysis when the farm is composed by 30 AWES.

Whatever the situation we take into account, it is clear from the graph that some factors are much more influential than others.
The AWES and the electrolyser contribute to the unit cost is about 80-93% of the total. The range is always respected, except when the farm comprises two AWE systems alone. Only in that case, the percentage descends below 80%. However, in every instance, as the farm gets bigger, the cumulative AWES and electrolyser percentage tends to rise (for equal sizing of the electrolyser). If we instead evaluate the single contributions of the two elements, it's possible to observe that, at first, the electrolyser contribution is the greater one. Later, though, the tendency reverses as a result of a considerable rise in the number of AWE systems and the amount of energy utilised. It is anyway reasonable to conclude that these factors are by far the ones that have the most impact on the unitary cost of hydrogen, regardless of which of the two components holds the major percentage (depending on the size).
Regarding BESS, much of its impact is determined by the specific dimensioning. As can be seen in the figures, the battery has a major impact when the number of AWES is small. In these cases, its influence on the unit price is quite significant, with values ranging between 15 and 25%. This is mostly caused by the expensive CAPEX, which is not balanced by production when there are only a few AWE systems. Although we must keep in mind the increases in battery power to 12 and 22 AWES, we can see how the BESS's influence steadily diminishes as the size of the farm grows. For the same reason, this also happens when the electrolyser's size switches to greater dimensions. Considering the above, it might be possible to consider adopting a different strategy in using BESS. Instead of using a discrete technique as has been done so far for batteries, you can consider using continuous sizing (as for the other components). A possibility might be to consider the BESS size equal to 10% of the AWES' nominal power. In this way, the idea of a safety buffer would be preserved, but at the same time, expenses would generally be smaller and proportional to the plant's production. This may reduce the impact on the unitary cost, especially for small plant sizes.
The contributions of water treatment, hydrogen storage and compressor are far lower. In the most significant case, their cumulative percentage is slightly below 5%. The CAPEX of these components is significantly lower, causing this discrepancy between the unitary cost percentages.

Following this analysis, it can be therefore concluded that the hydrogen's cost is mainly due to energy generation from the renewable source and the electrolysis process. The elements to work on to lower expenditures are, therefore, these two. However, it is possible to think that their future performance could be improved since they are both components still subject to research. In addition, the push given by the evolution of the hydrogen and RES market could allow a decrease in costs. It should also be noted that a more in-depth study of the BESS sizing could help in a unit cost further improvement.

# 5 | Conclusions and future developments

This study aims at providing a general but complete overview of an AWE offshore plant for hydrogen production. The first objective of this research was to identify all the components necessary for plant construction and to size them most suitably. This study employs AWE systems as an energy source since they allow hydrogen to be sustainable and green. Electrolysers and compressors are then highlighted as the most traditional elements for production. To these two elements has been added a desalination treatment, considering the needs of an offshore site, a space for hydrogen storage and BESS systems for emergency interventions, which are usually not taken into account. Focusing on the plant sizing, everything depends on the power provided by wind energy and on the electrolyser size. To maximise the amount of hydrogen produced, it is always preferable to size the electrolyser to the largest size compatible with the power of AWE systems. However, the investment increase with the electrolyser size and the unitary costs found during the study have highlighted how the most profitable dimension must be evaluated case by case. If we look instead at plant consumption, it is possible to state that the electrolyser uses the most energy. This demonstrates how the process is energetically costly. However, the efficiency employed in this analysis is that of present electrolysers ($\sim 80\%$), but these numbers might grow in 2040. There are currently studies underway with efficiency goals of 95–98%. This improvement would increase production for the same energy consumption and potentially lower expenses while confirming the plant's good quality. The second goal of this study was to estimate the unit cost of hydrogen to see how feasible a project of this nature might be. The obtained costs are comparable to or slightly higher than the future projections for the hydrogen market development in the analysed regions. This leads us to think that similar hydrogen production is feasible.

Future works could focus on possible improvements and insights to better detail this research and provide more accurate cost estimates. The first deepening could centre on the electrical connection between the AWE systems' platforms and the central production platform. This aspect has not been considered in this study, but it would add depth to the structure and cost analysis. In conjunction with this evaluation, further research into the BESS would be necessary to see whether proportionate dimensioning (e.g. 10% of the electrolyser power) may still perform well in favour of lower costs, particularly in small-scale farms. Additionally, it might be possible to improve the investigation of the hydrogen's transportation from the offshore site to the buyer. In particular, an infrastructure that would allow hydrogen to be transported straight from the platform to the ground could be significant. This connection might be extremely effective if the hydrogen economy will be extensively adopted. Finally, a feasibility analysis could also be carried out if liquid hydrogen is chosen instead of gaseous.

# Bibliography

[1] Skysails power. URL `https://skysails-power.com/`.

[2] O. Alnajdi, Y. Wu, and J. Kaiser Calautit. Toward a sustainable decentralized water supply: Review of adsorption desorption desalination (add) and current technologies: Saudi arabia (sa) as a case study. *Water*, 12(4), 2020. ISSN 2073-4441. doi: 10.3390/w12041111.

[3] J. Andersson and S. Grönkvist. Large-scale storage of hydrogen. *International Journal of Hydrogen Energy*, 44(23):11901–11919, 2019. ISSN 0360-3199. doi: https://doi.org/10.1016/j.ijhydene.2019.03.063.

[4] H. Barthelemy, M. Weber, and F. Barbier. Hydrogen storage: Recent improvements and industrial perspectives. *International Journal of Hydrogen Energy*, 42(11):7254–7262, 2017. ISSN 0360-3199. doi: https://doi.org/10.1016/j.ijhydene.2016.03.178.

[5] P. Bechtle and U. Zillmann. High-altitude wind energy map published, 1999. URL `https://airbornewindeurope.org/resources/high-altitude-wind-energy-map-published-2/`.

[6] C. N. Bonacina, N. B. Gaskare, and G. Valenti. Assessment of offshore liquid hydrogen production from wind power for ship refueling. *International Journal of Hydrogen Energy*, 47(2):1279–1291, 2022. ISSN 0360-3199. doi: https://doi.org/10.1016/j.ijhydene.2021.10.043.

[7] BVG Associates on behalf of Airborne Wind Europe. Getting airborne – the need to realise the benefits of airborne wind energy for net zero. Technical report, September 2022.

[8] A. Cherubini, A. Papini, R. Vertechy, and M. Fontana. Airborne wind energy systems: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 51:1461–1476, 2015. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2015.07.053.

[9] E. Comelli, ilSole24ore. Nascerà in sicilia il primo parco eolico galleggiante del mediterraneo, 2020. URL `https://www.ilsole24ore.com/art/`

nascera-sicilia-primo-parco-eolico-galleggiante-mediterraneo-ADIXfxX?refresh_ce=1#commentsform.

[10] Dupont. *FilmTec™ Reverse Osmosis Membranes Technical Manual*, 2022.

[11] L. Fagiano and S. Schnez. On the take-off of airborne wind energy systems based on rigid wings. *Renewable Energy*, 107:473–488, 2017. ISSN 0960-1481. doi: https://doi.org/10.1016/j.renene.2017.02.023.

[12] L. Fagiano, M. Milanese, and D. Piga. High-altitude wind power generation. *IEEE Transactions on Energy Conversion*, 25(1):168–180, 2009.

[13] L. Fagiano, M. Quack, F. Bauer, L. Carnel, and E. Oland. Autonomous airborne wind energy systems: Accomplishments and challenges. *Annual Review of Control, Robotics, and Autonomous Systems*, 5(1):603–631, 2022. doi: 10.1146/annurev-control-042820-124658.

[14] F. Felker. Makani's airborne wind power system takes flight offshore. URL https://medium.com/@fortfelker/makanis-airborne-wind-power-system-takes-flight-offshore-907fd4c9af86.

[15] C. Fritzmann, J. Löwenberg, T. Wintgens, and T. Melin. State-of-the-art of reverse osmosis desalination. *Desalination*, 216(1):1–76, 2007. ISSN 0011-9164. doi: https://doi.org/10.1016/j.desal.2006.12.009.

[16] S. Grigoriev, V. Fateev, D. Bessarabov, and P. Millet. Current status, research trends, and challenges in water electrolysis science and technology. *International Journal of Hydrogen Energy*, 45(49):26036–26058, 2020. ISSN 0360-3199. doi: https://doi.org/10.1016/j.ijhydene.2020.03.109.

[17] H-TEC Systems. H-tec pem electrolyzers hcs. URL https://www.h-tec.com/en/products/detail/h-tec-pem-elektrolyseur-hcs/10-mw-hcs.

[18] M. Hermesmann and T. Müller. Green, turquoise, blue, or grey? environmentally friendly hydrogen production in transforming energy systems. *Progress in Energy and Combustion Science*, 90:100996, 2022. ISSN 0360-1285. doi: https://doi.org/10.1016/j.pecs.2022.100996.

[19] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. Era5 hourly data on single levels from 1959 to present. copernicus climate change service (c3s) climate data store

(cds). 2018. URL https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.

[20] N. Hydrogen. Water electrolysers / hydrogen generators. URL https://nelhydrogen.com/water-electrolysers-hydrogen-generators/.

[21] IRENA. Hydrogen from renewable power: Technology outlook for the energy transition. Technical report, International Renewable Energy Agency, 2018. Abu Dhabi.

[22] IRENA. World energy transitions outlook 2022: 1.5°c pathway. Technical report, International Renewable Energy Agency, 2018. Abu Dhabi.

[23] IRENA. Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5c climate goal. Technical report, International Renewable Energy Agency, 2020. Abu Dhabi.

[24] IRENA. Global hydrogen trade to meet the 1.5°c climate goal: Part iii – green hydrogen cost and potential. Technical report, International Renewable Energy Agency, 2022. Abu Dhabi.

[25] IRENA. Global hydrogen trade to meet the 1.5°c climate goal: Part i – trade outlook for 2050 and way forward. Technical report, International Renewable Energy Agency, 2022. Abu Dhabi.

[26] M. LLC. The green hydrogen economy - predicting the decarbonisation agenda of tomorrow. URL https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html.

[27] M. L. Loyd. Crosswind kite power (for large-scale wind power production). *Journal of energy*, 4(3):106–111, 1980.

[28] T. R. Lucas, A. F. Ferreira, R. Santos Pereira, and M. Alves. Hydrogen production from the windfloat atlantic offshore wind farm: A techno-economic analysis. *Applied Energy*, 310:118481, 2022. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2021.118481.

[29] K. Meier. Hydrogen production with sea water electrolysis using norwegian offshore wind energy potentials. *International Journal of Energy and Environmental Engineering*, 5, 2014. ISSN 2251-6832. doi: https://doi.org/10.1007/s40095-014-0104-6.

[30] K. Park, J. Kim, D. R. Yang, and S. Hong. Towards a low-energy seawater reverse osmosis desalination plant: A review and theoretical analysis for future directions.

*Journal of Membrane Science*, 595:117607, 2020. ISSN 0376-7388. doi: https://doi.org/10.1016/j.memsci.2019.117607.

[31] G. Sdanghi, G. Maranzana, A. Celzard, and V. Fierro. Review of the current technologies and performances of hydrogen compression for stationary and automotive applications. *Renewable and Sustainable Energy Reviews*, 102:150–170, 2019. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2018.11.028.

[32] Siemens energy. Silyzer 300 datasheet, 2020. URL `https://assets.siemens-energy.com/siemens/assets/api/uuid:a193b68f-7ab4-4536-abe2-c23e01d0b526/datasheet-silyzer300.pdf`.

[33] M. Stevens and P. Smulders. The estimation of the parameters of the weibull wind speed distribution for wind energy utilization purposes. *Wind Engineering*, 3(2): 132–145, 1979. ISSN 0309524X, 2048402X. URL `http://www.jstor.org/stable/43749134`.

[34] Thomas D. (Hydrogenics), Mertens D. (Colruyt), Meeus M. (Sustesco), Van der Laak W., Francois I. (WaterstofNet). Power-to-gas roadmap for flanders. Technical report, Brussels, 10 2016.

[35] C. Van Leeuwen and A. Zauner. D8. 3—report on the costs involved with ptg technologies and their potentials across the eu. *EU Horizon*, 2020.

[36] C. Vermillion, M. Cobb, L. Fagiano, R. Leuthold, M. Diehl, R. S. Smith, T. A. Wood, S. Rapp, R. Schmehl, D. Olinger, and M. Demetriou. Electricity in the air: Insights from two decades of advanced control research and experimental flight testing of airborne wind energy systems. *Annual Reviews in Control*, 52:330–357, 2021. ISSN 1367-5788. doi: https://doi.org/10.1016/j.arcontrol.2021.03.002.

[37] L. Vidas, R. Castro, and A. Pires. A review of the impact of hydrogen integration in natural gas distribution networks and electric smart grids. *Energies*, 15(9), 2022. ISSN 1996-1073. doi: 10.3390/en15093160.

[38] WWF - World Wide Fund for Nature. Maritime traffic. URL `https://www.wwfmmi.org/medtrends/shifting_blue_economies/maritime_traffic/`.

[39] ZEFIRO VENTO S.r.l, Stantec S.p.A. Parco eolico offshore "zefiro" nel mar tirreno, sardegna nordorientale. Technical report, Copenhagen Energy A/S, 2022.

[40] J. Z. Zhang, J. Li, Y. Li, and Y. Zhao. Established methods based on compression and cryogenics. In *Hydrogen generation, storage and utilization*, chapter 5. John Wiley & Sons, 2014.

# List of Figures

# List of Tables

# List of Symbols

| Variable | Description | SI unit |
|---|---|---|
| $C_{BESS}$ | BESS total cost | € |
| $C_{COMP}$ | Compressor total cost | € |
| $C_{EL}$ | Electrolyser total cost | € |
| $C_{ENERGY}$ | Energy total cost | € |
| $C_{FIXED}$ | Total fixed costs | € |
| $C_{H_2}$ | Cost for 1 kg of hydrogen | € |
| $C_{ST}$ | Storage total cost | € |
| $C_{STACK}$ | Stack replacement cost | € |
| $C_{TOT}$ | Total costs | € |
| $C_{WT}$ | Water treatment cost | € |
| $CAPEX_{COMP}$ | Compressor CAPEX | € |
| $CAPEX_{EL}$ | Electrolyser CAPEX | € |
| $CAPEX_{WT}$ | Water treatment CAPEX | € |
| $cons_{TOT}$ | Annual energy consumption | kWh |
| $E_{COMP}$ | Compressor unitary energy consumption for 1 kg of hydrogen | $kWh/kg$ |
| $E_{EL}$ | Electrolyser unitary energy consumption for 1 kg of hydrogen | $kWh/kg$ |
| $E_{H_2O}$ | Energy consumed to desaline 1 $m^3$ of water | $kWh/m^3$ |
| $E_{WT}$ | Water treatment unitary energy consumption for 1 kg of hydrogen | $kWh/kg$ |
| $E_{YEAR}$ | Energy production of AWE in one year | $kWh$ |
| $E_{TOT}$ | Total unitary energy consumption for 1 kg of hydrogen | $kWh/kg$ |

| Variable | Description | SI unit |
|---|---|---|
| $f_{H_2}$ | Maximum hydrogen flow | $kg/s$ |
| $f_{H_2O}$ | Maximum water flow needed | $m^3/s$ |
| $n_{KITE}$ | Number of AWE systems in the farm | $-$ |
| $OPEX_{COMP}$ | Compressor OPEX | € |
| $OPEX_{EL}$ | Electrolyser OPEX | € |
| $OPEX_{WT}$ | Water treatment OPEX | € |
| $P_{SAT}$ | Input power saturation | $kW$ |
| $P_{KITE_{NOM}}$ | Nominal AWE system power | $MW$ |
| $Q_{H_2}$ | Hydrogen production in one year | $kg$ |
| $S_{BESS}$ | BESS size | $MW$ |
| $S_{COMP}$ | Compressor size | $kW$ |
| $S_{EL}$ | Electrolyser size | $kW$ |
| $S_{ST}$ | Storage size | $kg$ |
| $S_{WT}$ | Water treatment equipment size | $kW$ |
| $W_{H_2O}$ | Water necessary for 1 $kg$ of hydrogen | $m^3/kg$ |

# List of Acronyms

| Acronym | Description |
| --- | --- |
| AEM | Anion Exchange Membrane |
| AWE | Airborne Wind Energy |
| AWES | Airborne Wind Energy System |
| BESS | Battery Energy Storage System |
| CAPEX | CAPital EXpenditure |
| COPV | Composite Pressure Vessels |
| DECEX | DECommissioning EXpenditure |
| DEVEX | DEVelopment EXpenditure |
| LCOE | Levelized Cost Of Energy |
| LCOH | Levelized Cost Of Hydrogen |
| NL | Nominal Load |
| OPEX | OPerational EXpenditure |
| PEM | Polymer Electrolyte Membrane |
| RES | Renewable Energy Sources |
| RO | Reverse Osmosis |
| SOEC | Solide Oxide Electrolysis Cell |
| SWRO | SeaWater Reverse Osmosis |
| TDS | Total Dissolved Units |

# Acknowledgements

Il primo ringraziamento va al professor Fagiano, per avermi dato la possibilità di lavorare su un argomento tanto interessante. Grazie per il costante aiuto ricevuto durante questi mesi di lavoro e per la sua disponibilità. Mi è stato detto più volte di cercare un relatore che potesse offrire non solo un argomento interessante, ma anche un contributo personale al percorso di studi. Credo di aver fatto la scelta giusta.

Un grandissimo grazie alla mia famiglia, che ha permesso che tutto questo fosse possibile e mi ha sempre lasciata libera di seguire la strada più adatta a me. Mi avete supportata in ogni momento senza avere mai dubbi su quello che stessi facendo. Per questo vi sono enormemente grata. Grazie mamma per avermi insegnato a dare il massimo e a credere nel mio potenziale, tenendo sempre conto dell'importanza di prendersi cura di se stessi. Grazie papà per aver sempre creduto nelle mie possibilità, spesso più di quanto facessi io stessa. Grazie Sara perchè sei un modello per me, piena d'idee (sempre tutte in ordine) e disposta a dare il massimo per tutti. Il tuo sostegno e i tuoi consigli sono stati cruciali in tanti momenti di questo percorso. Grazie anche a Roberto, ormai un po' un fratello acquisito, per aver contribuito nel creare tanti bei momenti che mi aiutassero a staccare la testa dagli impegni universitari.

Grazie a Ivan per essere un compagno così speciale e prezioso. Grazie perchè sei il mio fan numero uno. Non hai smesso neanche un secondo di credere che potessi raggiungere ogni obiettivo e anche nei momenti più bui hai saputo trasmettermi tutta la fiducia che hai in me. Mi sei sempre stato accanto, vicino vicino quando mi serviva una spalla a cui appoggiarmi, un passo di fianco quando avevo bisogno della tua presenza ma sapevi che le decisioni spettavano a me e a nessun altro. Hai trovato ogni volta la giusta distanza per farmi stare al meglio, ma non c'è mai stata una volta in cui ti abbia sentito troppo lontano. Grazie perchè ogni giorno vedo tutto il tuo impegno nel cercare di rendermi serena e strapparmi un sorriso. Mi rendi felice e anche se capita che le nostre teste dure si scontrino, so che ogni volta ne usciamo migliori di prima. Non vedo l'ora di costruire ricordi con il mio dottore e di raggiungere nuovi traguardi insieme, possibilmente sopra i 3000 metri!

Grazie a Fabio con cui ho condiviso questo percorso dal primo fino all'ultimo giorno (letteralmente). Grazie per tutte le ore di studio passate insieme, talmente tante che sono difficili da quantificare, e grazie per il sostegno e la pazienza che hai sempre avuto. Grazie perchè non c'è stata volta in cui non mi hai sostenuta prima di un esame, ripendendomi infinitamente "dai, che sai tutto!" e prendendo in giro le mie mille paranoie per strapparmi un sorriso in mezzo all'agitazione. Grazie perchè alla fine di quegli esame hai passato minuti e minuti ad ascoltarmi, concludendo sempre con "al massimo lo riprepariamo insieme al prossimo appello" per rendermi più tranquilla. Mi hai insegnato che abbiamo la forza per fare tutto quello che vogliamo e che per nessun motivo dobbiamo pensare di essere inferiori agli altri. Perchè anche con qualche 30 in meno, siamo all'altezza di raggiungere ogni obiettivo. Ti voglio bene, anche se te l'ho detto poche volte.

Grazie a Giulio per esserci sempre stato in questi anni e aver condiviso con me tanti momenti e riflessioni importanti. Insieme a lui, voglio ringraziare anche Davide per il supporto e perchè so che su di lui posso sempre contare. Grazie a voi per le mille risate, per tutte le serate passate insieme tra discorsi seri e altri un po' meno, per le notti trascorse a giocare online durante il lockdown e per le nostre cenette dal calabrese. Mi avete regalato la leggerezza necessaria per superare i momenti più stressanti.

Grazie a Filippo per aver condiviso con me questi 5 anni. Sei una gran testa dura, ma la tua bravura e la tua dedizione (so che c'è anche se tu spesso non la ammetti) sono state per me un esempio.

Grazie a Giulio M. per l'enorme supporto durante l'ultima e impegnativa sessione d'esame. Mi hai dato un aiuto che nessun'altro sarebbe stato in grado di darmi, anche nelle situazioni più complicate e per questo non smetterò mai di ringraziarti.

Grazie ad Arianna e Rossella, entrambe amiche incontrate sui campi da pallavolo. Loro non si conoscono, ma entrambe mi hanno fatto capire bene cosa significa esserci nel momento del bisogno. Possiamo anche trovarci a chilometri di distanza o non sentirci da giorni, ma so che ogni volta che mi servirà qualcosa, loro saranno sempre disposte a dare una mano.

Grazie a Noemi, Aurora e Silvia per avermi accompagnata nella mia lunga carriera scolastica, dal liceo fino ad oggi.

Grazie infine a tutte le persone che qui non sono citate (i ringraziamenti erano già lunghi abbastanza), ma che hanno in qualche modo hanno fatto parte del mio percorso. Penso che ognuno di voi abbia contribuito a farmi diventare la persona che sono oggi.