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Executive Summary of the Thesis

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

Laurea Magistrale in Automation and Control Engineering - Ingegneria dell'Automazione

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1. Introduction

Climate change is profoundly changing our planet. For more than a hundred years, we have been observing a marked rise in the average temperature and the frequency of extreme weather. These phenomena originate from the continuous emissions of CO_2 into the atmosphere since the industrial revolution. Therefore, man and his activities are the cause of this transformation. And because of the habits he has developed, man is the only one who can stop this trend and save the environment. The United Nations Framework Convention on Climate Change (UNFCCC) established the objectives of limiting global temperature rise to 1.5 Celsius degrees with respect to pre-industrial levels and achieving net zero emissions by the year 2050. Six principal methods can be used to carry out these agreements: use of renewable resources, electrification, development of a hydrogen market, efficiency of energy processes, carbon capture and storage and bioenergy coupled with carbon capture and storage (BECCS).

Hydrogen, in particular, could be a crucial help in making sustainable sectors hard-to-abate, such as heavy industry and transport. Its use might help reach the objective of net zero emissions by almost 10%. By the way, the unavoidable requisite for hydrogen exploitation is that it is green, i.e., produced from electrolysis and renewable energy sources. To be effective for the energy transition and enable the creation of a hydrogen market, green hydrogen production must increase from its current 4% to the total. The cost of hydrogen, which is around 5 €/kg, is the other factor that prevents its diffusion at the moment. However, because lowering emissions is so important, in the coming years, there will be a reciprocal relationship between rising demand and falling prices that will result in production costs between 0.75 and 1.5 €/kg.

Regarding renewable resources, solar and wind power will primarily replace fossil fuels. Looking at wind energy, there is a developing technology that offers several benefits against conventional wind turbines: the airborne wind energy (AWE) systems. Their basic principle consists in exploiting medium-high altitude wind to fly tethered airfoils connected to a ground station with a cable. The ability to fly to higher heights than the turbines, the simple structure, flexibility and low cost make AWE systems particularly intriguing and with great potential.

This study examines the structure of a green hydrogen production plant using offshore AWE. This research also realises a cost analysis in four locations of interest to determine whether such a project is feasible. The goal is to advance research on hydrogen and renewable resources, connecting these two fields to aid in the ecological transition.

2. System description

The first step in conducting this study is the identification of the components for the plant's proper operation. These elements must include everything necessary for energy production, hydrogen generation and storage. Figure 1 shows the plant structure and the interaction between parts.

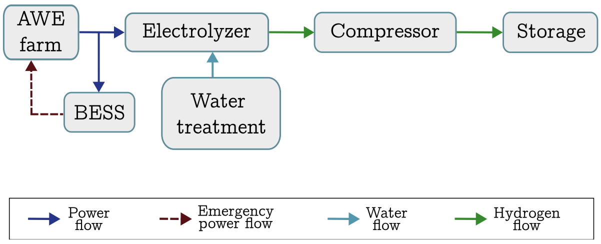

Figure 1: Plant scheme and interaction between components.

Energy production takes place using AWE systems. Such systems, as described in introduction, enable power generation from wind speed, producing energy sustainably. This study considers employing an offshore AWE farm to supply the hydrogen production plant.

If we instead focus on the hydrogen generation process, the two essential parts are the electrolyser and the water treatment system. The first is the equipment that enables water to be divided into hydrogen and oxygen using a basic chemical reaction propelled by electricity. Polymer electrolyte membrane (PEM), one of the many electrolyser technologies available, was selected for this study. This type of electrolyser is one of the most developed and provides the best performances. Then, to achieve the levels of water purity required for the electrolysis process, water treatment is a necessity. It was decided to use seawater directly, desalinating it on-site since the plant is offshore. Seawater reverse osmosis (RO) is the treatment chosen in this situation, allowing for the separation of the water from its salty component and other solutes.

The first decision for transport is to keep hydrogen in the gaseous state. However, hydrogen has a low volumetric density despite a high energy density. This means the gas must be compressed before being transported to maximise the space occupation. Consider that 220 bar is the maximum safe pressure for transport across medium to long distances. A compressor is therefore required to bring hydrogen from the electrolyser's exit pressure to this level. The choice for this plant falls on a two-stage reciprocating compressor, a mature technology that respects the pressure range required. This compressor works by cycling a piston, reducing the volume of gas until the pressure reaches 220 bar. Gas is then stored in cylinders, which can be of several types: I, II, III and IV. The ones chosen for this work are type I, which are made of metal and have pressure tolerance appropriate for our needs. Although alternative varieties are also being developed, type I currently give a superior value for the money. The tanks will be ready for withdrawal by the hydrogen-carrying vessels once filled.

A battery energy storage system (BESS) is the final addition to the system. Its integration into the structure was primarily decided for safety reasons. The AWE systems, in fact, do have a retraction phase in their production cycle. This phase is essential to the operation of the kite but demands energy, although it's a small portion of the energy produced. The AWE systems, which are always present in groups of at least two, are offset so that the energy requirement of one kite is met by the production of the other. However, any issues could result in a lack of compensation and erroneous system operation. BESS mostly work as a security buffer, which can intervene in an emergency or balancing failure.

3. Locations

It was decided to select four places to test our system to conduct a more thorough investigation and utilize specific wind speed data. These sites, as showed by figure 2, are:

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

These areas were selected based on two key factors. Hornsea One and Viana Do Castello already have conventional wind farms. This assured us that the outcomes were only a function of the system's reliability and not the wind's goodness. Then, Marsala and Olbia were chosen by comparing the wind data in the Mediterranean Sea and the major commercial routes. In addition to having a favourable average wind speed, the two locations are also great maritime traffic centres, thus facilitating the movement of ships transporting the hydrogen from the platform to the consumer.

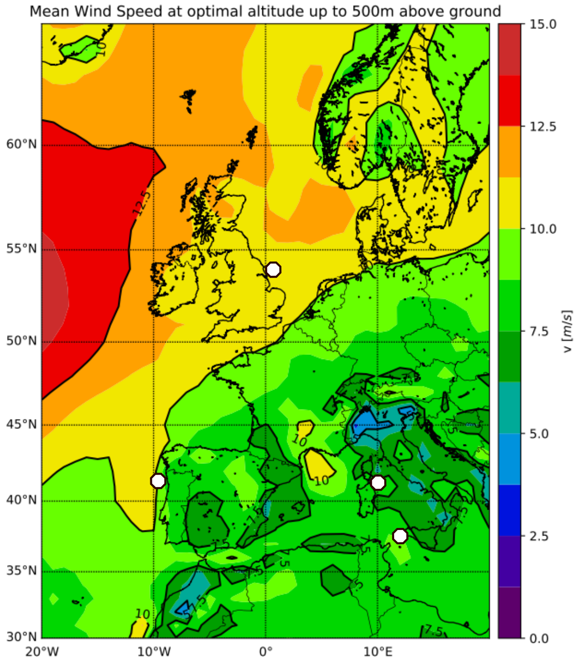

Figure 2: Chosen locations and wind speed mean at an optimal altitude up to 500m [1].

The wind intensities in the four locations are extrapolated from ERA5, a database containing global climate and weather information from 1950 to the present [2].

4. System model

Once all of the system's parts have been identified, it's necessary to comprehend how to size each element and evaluate the production output in the selected cases.

4.1. Sizing

The sizing of all plant components is dependent on AWE systems. The energetic flow needed for the electrolyser, water treatment, compressor, storage, and BESS depends on the AWE generation.

This research evaluates more than one size of an AWE farm to provide a comprehensive analysis. Considering an AWE system with a rated power of 1.1 MW as a base unit (power curve in figure 3), we will analyse all cases between 2 and 30 AWE systems, with a step of 2 units at a time.

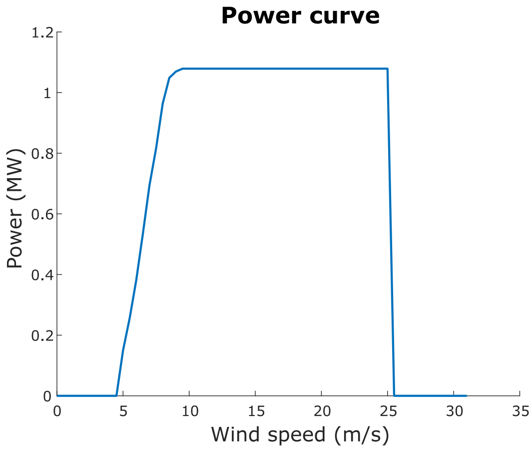

Figure 3: Power curve of a 1 MW AWE system.

The electrolyser is the second component to be examined for plant sizing after the AWE systems. Even in this instance, we select multiple possible sizes rather than just one scenario. We specifically employ three dimensions, equivalent to 90%, 73%, and 45% of the wind farm's total rated power. Since the production provided by the wind intensity is not constantly at its peak, it is decided to examine these various scenarios since sizing an electrolyser larger than needed could fail to recoup its expenses. At the same time, under-dimensioning might cause losses in production and profit. These different situations allow us to understand what's better to do.
Then, the electrolyser and AWE farm are used to size the remaining plant components. The size of the water treatment system is determined by the maximum quantity of work it must perform. Based on the knowledge that approximately 16 litres of water are required to produce one kilogram of hydrogen, we estimate the maximum water flow required by the electrolyser, i.e., the flow of water required when the electrolyser operates at its full capacity. From here, we can determine the desalination plant dimension by multiplying the energy consumption for the process ($4\ kWh/m^3_{H_2O}$) for this flow. Similar logic is used for the compressor. In this case, we multiply the maximum hydrogen flow from the electrolyser by the compressor's unit energy

consumption, given by the following equation.

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

where n is the number of compression stages, γ is the specific heat ratio, R_{H_2} is the ideal gas constant, T_{IN} is the temperature at the compressor inlet, η is the compressor efficiency, P_{OUT} is the output pressure and P_{IN} is the input pressure [3, 4].

The storage is sized to have a maximum daily capacity for production. It is assumed that the flow of hydrogen-carrying ships is such as not letting the accumulation of quantities bigger than the daily to limit the area occupied at sea.

Finally the BESS systems are sized following the rule:

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

where S_{BESS} is the size of the BESS and n_{AWES} is the number of the AWE systems in the farm. This rule was chosen to provide sufficient power to AWE systems in an emergency, considering the increasing demand with the size of the farm.

Once all the system components and their size are available, it's possible to analyse the consumption necessary for the production of one kilogram of hydrogen. Table 1 shows that the electrolyser, compressor, and water treatment are the three elements that have an impact on consumption. The electrolyser, which uses 97% of the available energy, dominates this value. Therefore, electrolysis is significantly more expensive than the other processes.

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

Table 1: Impact of each element on the consumption required to produce one kilogram of hydrogen.

4.2. Wind analysis

The ERA5 databases' wind data were analyzed before the annual hydrogen production was calculated. The seasonal trend of wind intensity was initially assessed for each of the four places, revealing a general trend: winter has the best values, summer has the worst, and autumn and spring stand at intermediate speeds. Additionally, this information has given us a preliminary impression of how good the selected places are. After that, the probability density function for each of the farms was determined. This curve permits us to show graphically the probability of having a certain wind speed over time. Knowing these probabilities and extrapolating from the power curve which speed intervals are productive and which are not, we calculated the percentage of productive and non-productive time for each location. Table 2 shows the results.

location	Productive	Unproductive
Location 1	84.07%	15.93%
Location 2	73.21%	26.79%
Location 3	70.18%	29.82%
Location 4	67.08%	32.92%

Table 2: Percentages of time in which the AWE systems are productive or not.

It is visible that Hornsea One, which is the first location, is performing far better than the rest. In contrast to the two Mediterranean locations, which are undoubtedly less prolific, location 2 (Viana do Castello) also produces good results.

4.3. Hydrogen production

The estimation of annual output comes after the wind analysis. First, the GWh output of AWE systems was determined. It can be obtained by simply matching the power curve of the AWE system with the probability density function. These values represent how well the various locations perform depending on wind intensity. Additionally, they are affected by the scale of the farm: the more AWE systems there are, the higher the productivity.

Then, we can examine the hydrogen production quantities. The power curve must first be saturated with a value equal to the electrolyser's nominal power plus the power of the compressor and the water treatment system. The plant will utilise this amount of power to a maximum. If the AWE system production exceeds this amount, firstly, the energy recharges at the BESS, and then when the storage is full, the electricity produced is discarded. Once the curve is saturated, it's possible to use it to determine how much energy is consumed annually. One may then determine the annual hydrogenproduction by knowing the energy needed to produce one kilogram of hydrogen.The obtained results vary based on location, farm size, and electrolyser size from $140 \cdot 10^3$ to $3900 \cdot 10^3$ kg. However, it is possible to recognise recurring trends in these data. First of all, the output confirms the earlier examination of the wind quality in various areas. The location is more productive the more favourable the wind values are. The farm that produces the most hydrogen is indeed Hornsea One. The second factor is that productivity rises as electrolyser size does. This results directly from the fact that larger electrolyser sizes enable greater utilisation of AWE systems, whereas smaller sizes result in significant energy loss.

As for the uses for such amounts of hydrogen, we can claim that such production is adequate to run a modest factory or car refuelling station. Therefore, production doesn't seem to be so significant. However, it should be remembered that all of the component features are evolving. For example, the electrolyser's performance could be improved in future, enabling a rise in production.

5. Cost analysis

The cost analysis is the final study to be carried out. Understanding the economic side is crucial to determining how much will be spent and whether it will be covered throughout the plant's lifetime.

The costs of each part were examined first. We must be clear that while the prices of the other components are current, those of the AWE and electrolyser is an estimate for 2040.

Regarding AWE systems, the cost of installation is not regarded as a direct cost but rather as the levelized cost of energy (LCOE) in 2040, which already includes the initial expenses (CAPEX), operational costs (OPEX) plus development costs (DEVEX).

The electrolyser's expenses depend on the size. The cost per kW starts at around 760 €/kW and drops as the scale increases, dropping at 550 €/kW for installations exceeding 10 MW. Operational costs are about 5% of the previous ones. Since the electrolyser's stack has a limited lifetime, we must consider at least two stack replacements.

The compressor operates on a very same principle: as size increases, the cost per kW decreases. In this instance, the entire cost is represented using the formula below.

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

The operational costs are 3% of the CAPEX, and we need to consider a replacement of the compressor during the 20 years horizon.

As for water treatment, capital expenditures costs are 1313 $\frac{€}{m^3/day}$, while the operational are about 6% of CAPEX.

The calculation of storage cost is simple as it uses a value of 225€/kg.

Finally, the BESS cost is interpolated from values provided by a supplier. The results are 2 212 587 € for 1 MW, 3 725 381 € for 2 MW and 4 538 381 € for 3 MW.

After seeing every cost, we can add them to get the total expenditure over the next 20 years. Once this is done, we can estimate the levelized cost of hydrogen (LCOH) by dividing the entire cost by the total production. In this way, we get the unitary costs for each location for the different plant sizes. The costs obtained range from 3.50 to 1.90 €/kg. However, prices exceeding 2.50 €/kg are exclusive of small plants, whose development is significantly less likely than that of medium-sized farms.

Costs exhibit some properties, in the same way as observed for the quantity produced. Firstly, the lowest costs are in the best location for wind intensity, namely the Hornsea One. All other sites have higher costs, which grow in inverse proportion to the goodness of the wind. Costs do not, however, drop in line with the trend that the increase in the electrolyser's size produces more hydrogen. In fact, especially for the large sizes of wind farms, the unit cost grows with the size of the electrolyser, although this increase is only a few cents. This is due to the difference in the amounts of hydrogen produced between various sizes being insufficient to compensate for the increase in investment. Therefore, depending on whether a slight price rise can be tolerated in face of increasing production, the larger sizing can be more or less ideal. It results that the optimum sizing is never the same for every situation, but each situation must be evaluated individually.

In terms of unit cost valuation, we can state that the range of values discovered is reasonably close to the projections made by other studies. Some values are marginally higher, however, it is important to take into account possible future machinery efficiency improvements as well as the fact that not all of the prices included in this research are projected for 2040-2050. Enhancements in these fields can cause the LCOH to drop even further.

6. Conclusions

The work objective was to assess the structure of a hydrogen production plant using offshore AWE systems and to evaluate production and costs.

In the project, every potential plant component has been investigated to determine the optimum technologies to employ. After that, each piece of equipment was dimensioned. This operation allowed us to assess the structure of the plant in different situations and locations and establish the amount of hydrogen produced. Finally, we computed the unitary cost of hydrogen for each location and dimension based on capital and operational expenditure and the total yearly production.

The outcomes seem to be a similar representation of future cost projections. Even while the Mediterranean areas perform worse than the others, we can still state that the unit cost is within or a little bit beyond the range anticipated (0.75-2 €/kg). The research thus supports the initial hypothesis and suggests a potential application for such a plant in the generation of green hydrogen.

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