Department of Mechanical Engineering

Hybrid energy system in power plant

Author: Menelaos Tamvakologos

Supervisor: Robert McLean

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Signed: Menelaos Tamvakologos Date: 19.12.10

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1. Abstract

Electricity is an essential commodity for modern people and it is very important for the future development of the society. This good must be supplied on a continuous basis in order to cover the daily requirements. Power plants are the only way to insure the daily production of electricity; however, they contribute significantly to environmental pollution, since they consume fossil fuels.

This project investigates ways to operate a combined cycle power plant using renewable energy sources which offer fuel independency, secure continuous functioning and most importantly produce no gas emissions.

The aim is to take advantage of every available renewable energy source (sun, wind, water, earth) and to convert it into hydrogen for the power plants fuel consumption, as well as to exploit solar or geothermal energy to support the steam generation for the heat recovery system or for an auxiliary boiler.

A combined cycle power plant unit (5+2 MW) is capable of supplying, in theoretical basis, a small community in Cyprus with electricity. The fuel requirements of the gas turbine are covered by hydrogen, which is produced from electrolyzers that consume electricity generated in a wind farm, while the solar panels heat water in order either to reinforce the steam that is produced in the heat recovery steam generation system or to support an auxiliary boiler for the needs of the power plant.

Homer simulation programme has been used for the planning of the gas turbine/wind-farm/hydrogen system, such as: sizing the wind-hydrogen system so as to cover the annual gas turbine fuel consumption, estimating the amount of CO_2, CO and NO_x savings and calculating the economic viability of the system. Also, a Microsoft Excel document has been used for a number of equations for the solar system.

2. Acknowledgements

I would like to thank Dr Robert McLean who accepted to supervise my "hybrid energy system in a power plant" idea and guide me for the project outline. I would like to wish him happy retirement years. And finally, I would like to thank Rototech Company (http://www.rototech.gr/) for the help and the information they gave me for the completion of my thesis.

Table of Contents

List of Figures

3. Introduction

3.1 Project Overview

The global population increase has created the need of more energy resulting, for the developed countries, in either investing in the construction of new power plants or extending the operation of the existing ones. In addition and due to the global commitments for CO_2 reduction, the majority of the new energy project investments are recommended to be for renewable sources of energy.

Also, since many countries don't have primary production of fossil fuels, the occasional instability of the oil prices has created the need of fuel independency. However, renewable sources of energy are abundant and many countries can take advantage by exploiting them in order to either produce electricity directly, or transform them into hydrogen for fuel usage.

This project is trying to approach the issue of power production from a different perspective, combining conventional with alternative methods, targeting in the best result. It was inspired by the global economic policy, which makes it difficult for most countries to take drastic measures to address pollutants while looking for alternative ways of massive power production.

The main issue of the project is to integrate renewable energy systems in power plants in order to take advantage of the benefits of abundant and clean energy sources. The reduction of CO_2 emissions, the partial independency from fossil fuels and the increase of energy generation are some of the benefits that are investigated in this project.

The case study is taking place in the island of Cyprus a choice that meets all of the above preconditions such as the fuel dependence on other countries, the needs of increasing its power generation and the commitments to the European Union for renewable power production. Thus, Cyprus has set as a short-range target to produce the 6% of the total electricity from renewable sources until 2010 while a long-range target is set to 13% until 2020 [1].

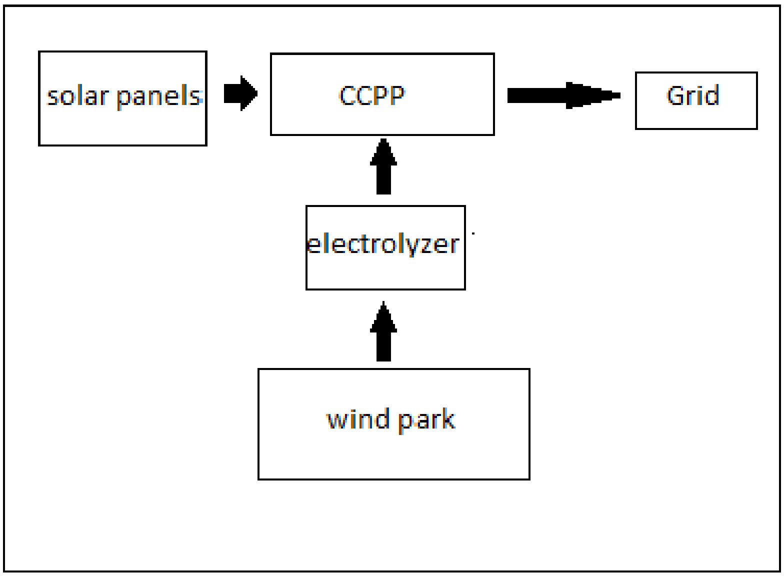


Figure 3.1: Diagram of the hybrid power station

Above figure 3.1 shows a diagram of the components that constitute this hybrid power station. During the day, solar panels heat the water inside the boiler in order to reduce the fuel consumption while the excess electricity produced by a wind farm supply the gas turbine.

3.2 Objectives and Methodology

The scope of the project is to evaluate theoretically the size of a hybrid energy system that supplies a combine cycle power plant (CCPP) all year round. The hybrid energy system consists of a wind-hydrogen system for the operation of a gas turbine while a solar panel system provides high heated water to the boiler of a steam turbine.

The objective is to replace the fossil fuel consumption with hydrogen, to provide fuel independency, to reduce the CO_2 emissions and to increase the power production from clean sources. All these will be compared to a corresponding conventional CCPP that is operating with fossil fuel. Finally, the case study aims to propose to Cyprus Government and its future plans an alternative investment for expansion of electricity generation based on renewable energy systems.

In Cyprus there is a large area which government plans to use for processing and storing fossil fuels. In this area has also been installed the bigger island's power plant. It is extremely polluted and the existing plan tends to make it even more difficult to reduce this pollution.

The problem in this project is indentified in the integration of the renewable hybrid system in the power plant due to the intermittent operation of the renewable sources. The wind-hydrogen system needs to be optimized in a level that always will supply the gas turbine while the solar field needs the right sizing in order to support alone the steam turbine.

The case study examines a simple model consisted of a small sized combined cycle power plant with the integrated renewable systems. Simple model offers a better definition of the system performance while at the same time is more accurate as far as the result analysis is concerned.

Briefly the key areas of the project are:

- To develop a hybrid energy system that integrates with a combined cycle power plant.

- To apply the system in a case study in order to evaluate the advantages and disadvantages.
- To make an analysis (economic, efficiency and CO_2 saving) that can bring out useful conclusions.

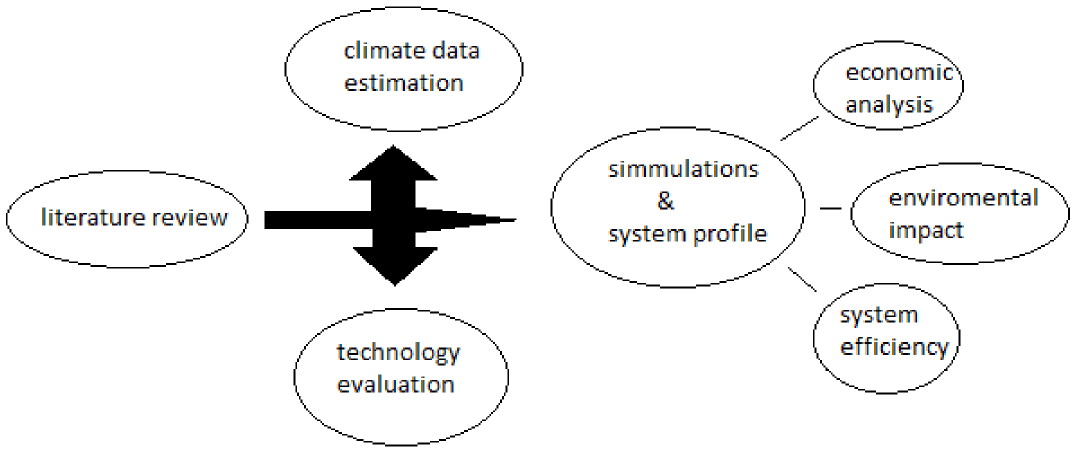


Figure 3.2: Diagram of the methodology

The above figure 3.2 shows a simple graph of the projects steps.

The idea was based on the integrated solar combined cycle power plant (ISCC), thus a literature review in order to briefly describe and understand the various system operations (similar systems and latest technologies) was considered necessary. Since the review is complete, climate data are collected to define the annual production of wind turbines and solar collectors.

Having collected the climate data, the selection of the wind/hydrogen and solar collector components is made. The selection is based on new technologies that contribute the maximum in order to have high efficient system.

At the end, the final system profile is set up through calculations and simulation programs. The analysis of the profile meets the key areas of the project while at the same time useful conclusions will be extracted.

4. Project Info

4.1 Hydrogen & Water Electrolysis

4.1.1 Introduction

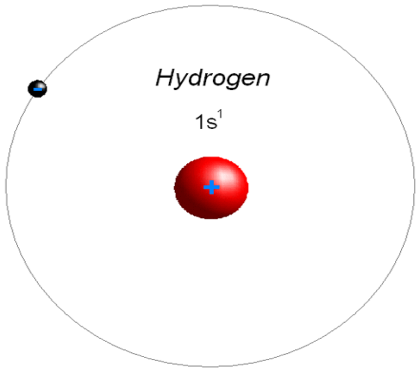
Nearly three decades ago, the lack of conventional fuels caused the energy crisis to the world, where 1973 appeared because of political options. It was then that many countries had realized that was depended only on conventional fuels and that it was essential the investment to alternative methods of energy production. Furthermore, in Kyoto was agreed from the majority of the countries that CO2 emissions are responsible for the greenhouse effect and that it is necessity the investment on renewable sources of energy. Thus, the researches in hydrogen technology have been started.

The hydrogen is the fuel that represents one of the most rapidly growing technologies in order to replace the conventional fuels. Although it is known for more than 100 years for its high flammable behavior, hydrogen technology started to develop only the last decades. The unique properties of hydrogen accomplish it as the fuel of the future which with uses in transportation and in energy production. Its high thermal value can drive all types of combustion engines while the zero carbon chemical composition is a direct solution for sustainable fuels.

The hydrogen production from renewable energy systems has proven to be reliable for energy independence, creating at the same time strong economies to countries. Unfortunately, only a 4% of hydrogen it is produced from renewable sources worldwide. It is essential then for a sustainable society which respects the environment, to replace the conventional fuels in hydrogen which will be produced exclusively from renewable source of energy.

The electrolysis is the simplest method to produce large quantities of pure hydrogen which has zero carbon emissions while also is a clean and reliable method. However, the viability of those systems depends on various economical criteria.

4.1.2 Hydrogen properties



Hydrogen is the most abundant element around the universe, as scientists estimate that a 75% of universe mass is hydrogen. The composition of hydrogen is very simple since one atom consists of a proton and an electron while a molecule is formed by two atoms.

The definition of the word "hydrogen" is derived from the Greek vocabulary, which describes one of its chemical properties which is the generation of water during the combustion of hydrogen. In standard conditions of temperature and pressure it has the form of non toxic gas which is lighter than the air.
Although hydrogen is everywhere in nature it is difficult to be found in its initial form because of its lightness. However, many elements contain hydrogen such as water, ammonia, several hydrocarbons (natural gas, oil) and general all the organic compounds.

One significant property of hydrogen is the flammability that shows when is mixed with air in high concentrations causing also explosions. Furthermore, in very high temperature hydrogen atoms are releasing significant amounts of energy. Thus, in the beginning of 18th century started to use hydrogen in industry, first in 1806 where was manufactured the first hydrogen combustion engine later in 19th century in zeppelins of its lightweight while nowadays it has several uses in industry and many methods of productions. .

A number of several key benefits of hydrogen create the interest for further investments in this technology [2]:

- It is the perfect fuel for the reduction of CO2 emissions. Since hydrogen and oxygen produce water the gas emissions can be reduced significantly renders it as the most environmental friendly fuel.

- It has high internal energy per unit of weight than any other fuel (120.7 kJ/gr), about three times more than oil. For this reason, it is diluted with steam or nitrogen (syngases) in order to reduce the heat during the combustion.

- It can be manufactured and consumed on site or it can be collected and distributed without significant losses, while the variety of hydrogen in nature facilitates its production.

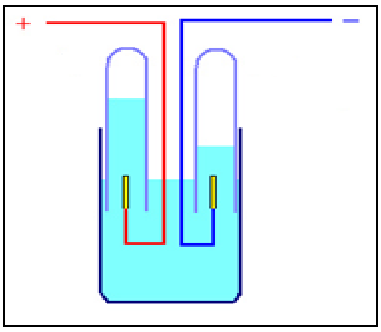
- It is easy in transportation, since it is very lightweight, having the form of gas or liquid. Also it can be combust by various types of engines and moreover it isn’t toxic in case of a leakage.

Nevertheless hydrogen technology has some crucial disadvantages which are under research:

- The amount of energy that is required in order to store the hydrogen is significant high.
- Need special materials since the atoms of hydrogen are very small and extremely kinetic and the conventional material have looses.

- All methods except from production from renewable energy sources, requires high amounts of energy that comes from conventional fuels, which means that the total efficiency of hydrogen is reduced significantly.

4.1.3 Hydrogen production



The fact that hydrogen exists in nature in several chemical compounds has create various methods of production and extraction.

- Chemical conversions

There are several chemical conversions techniques for hydrogen production such as the gasification, the steam reforming and the partial oxidation. The steam reforming and the gasification method are wide known and power plants have integrated such kind of units for their direct fuel supply. All hydrocarbons can be processed but the most efficient is the natural gas because it contains the higher proportion in hydrogen.

- Electrolysis of water

The electrolysis is a process that uses the electricity in order to split the water into hydrogen and oxygen, a procedure that take place inside an electrolyte. Today, small commercial electolyzers have applications in houses and in small industries for heat production but also larger electrolyzers have use in hydrogen supply stations for cars. The most commercial are the alkaline electrolyzer and the solid polymer electrolyzer (SPE), while other technologies such as solid oxyde electrolyzer are in research stage.
The electrolysis of water is a process that requires DC current and a suitable electrolyte. The DC current passes through two electrodes, one positively and one negatively charged, where are separated from the electrolyte. The positive ions of the hydrogen are attracted from the negative charged electrode while the negative ions of oxygen from the positive charged electrode.
The below figure 4.1 shows the chemical reaction of water:

Anode:	$2H_2O$	$\rightarrow 2H_2 + O_2$
Cathode:	$4H^+ + 4e^-$	$\rightarrow 2\,H_2$
Overall:	$2H_2\,O$	$\rightarrow 2\,H_2 + O_2$

Figure 4.1 : Hydrogen decomposition

The efficiency of an electrolyzer is related with the quantity of energy which turns into hydrogen. The production of hydrogen should be twice the production of oxygen and the overall effect to be proportional to the electric charge. Also is important to note that for the best efficiency of the system should use the appropriate combination of materials. Theoretically, for the electrolysis is required only 1,23V but for practical reasons is applied more voltage, thus if is applied 1,5 volts (V) the efficiency will be:

$$\frac{1{,}23}{1.5} = 0{,}82 = 82\%$$

- Thermolysis of water

This method requires significant amount of thermal energy to be spent in order to split hydrogen from water and scientists are experimenting to integrate such systems in new type of nuclear power plants.

- Photolytic process

The method takes advantage the power of sunlight but must be improved in order to be more efficient and competitive but it is well-promising method offering sustainable hydrogen production.

- Photolysis process

Several procedures of hydrogen production have been invented for biomass processing, wastes and algae but the most of them are in experimental stage.

4.1.4 Hydrogen storage

As all fuels, the hydrogen technology has also the need for storage in order to be transported and consumed. The most common methods of hydrogen storage that are used today is at high pressure tank and the conversion of hydrogen into liquid, while new methods such as metal hydrides, carbon nanotubes and chemical hydrides are very promising technologies but are in research stage.

- Methods that are using today

The tanks of high pressure have usage to store hydrogen in gas form at pressure from 200 (bar) to 700 (bar). The negative of this method is that the power that is required is very high with result to be reduced the efficiency of the system furthermore the dimension of the tanks must be extremely big.
The hydrogen storage in liquid form is preferred because is requires lesser space but also significant amount of energy has to be spent in order to cool and liquefy the hydrogen.

- Hydrogen storage tank of hydrides

The metal hydrides are combinations of different metals which are working as a sponge that absorb water. This method has the ability to absorb hydrogen and to emancipate it later with heat. The disadvantage of this method is that requires temperatures higher than 300 (^{0} C).
Same method but with different materials are used in carbon nanotubes technology where hydrogen is stored in very small pores of the metal tubes, however until now very small amounts of hydrogen have achieve to store.

4.1.5 Type of Electrolyzers

- Alkaline electrolyzers

The Alkaline electrolyzers are the most commercial, most developed and the oldest method for hydrogen production. The electrolyzer consists of from the cell, an electrolyte, two electrodes and the separator.

As electrolyte is usually used a solution of water which is mixed mainly with potassium hydroxide (KOH) at proportion of 25 – 30 wt%, also other substances have been used such as sodium chloride and sodium hydroxide. It must be noticed that the water solution needs replacement after some operation time because it loses their properties. The electrolyte enhances the conductivity of ions as the atoms of hydrogen and oxygen accumulate on the surface of electrode in order to form bubbles, which will rise up and collect in the surface of the solution.

The electrodes are the surface that the current is applied in order to create potential difference for the ions transportation. The most common material that is used is the nickel and the stainless steel because it has good conductivity and better resistance to the corrosion that cause the various solutions. The shape of the electrode is depending on the size and the shape of the electrolyzer.

The separator is a porous diaphragm which separates the cell in two areas. The diaphragm has very small pores in order to forbid the access of the bubbles from one area to the other, but to allow the access in both sides for the water solution. The material that usually is used is the asbestos because resists in corrosion.

A typical electrolyzer operates in pressure from 0 to 30 (bar) and in Dc current density from 100 to 400 (mA cm-2), while its efficiency fluctuates from 60% to 80%. The most advantaged electrolyzers are reaching the 90%. The hydrogen production from a normal electrolyzer can reach 10 (m^3/h), however large units can have 100 (m3/h) hydrogen production, while the purity of hydrogen reaches the 99.8% in volume.

There are two types of alkaline electrolyzers the unipolar and bipolar. The unipolar units consist usually by cells connected in parallel and operate at 1.8 – 2.5 (Vdc). The unipolar design overcomes to bipolar to the simple construction, the low cost and that it can be repaired without disturbing the operation of the other cells, while is handicap because of its big size and that operates in low pressure and temperature.

From the other side, the bipolar units are connected on series with result to operate in lower voltage stack and higher current density. Thus, it produces hydrogen in temperatures up to 150 (oC) and pressure 30 (bar). However, their operation is more expensive and in case of maintenance of a cell, the system must stop its operation.

- Solid Polymer electrolyzers

The Solid Polymer electrolyzers (SPE) are also known as proton exchange membrane fuel cells (PEM). This type of electrolyzer is many years now a reliable technology and very popular in the industrial applications. First was developed for production of oxygen in submarines, while NASA uses it for the same reason to spacecrafts. It is very friendly to the environment because in comparison with the alkaline electrolyzer doesn't uses acid solutions in electrolyte.

The cell is separated from a thin solid membrane which has the two electrodes attached in each side. The membrane is a good ion conductor and resists to electricity, while it blocks the access of the hydrogen gas and water from one to the other side. Actually, the membrane helps the hydrogen protons to pass from one electrode to other. Many materials have been used for membrane construction but the most common is the nafion.

The SPE electrolyzers are designed similar to bipolar but unlike alkaline electrolyzers they use water on high purity instead of water solution. The efficiency of these systems can reach 100% producing hydrogen in purity of 99,9% by volume.

Compared with alkaline electrolyzers they provide higher efficiency, they are more reliable and safer. They operate in current density higher than 1600 (mA cm-2) while the low stack densities makes the systems less expensive of the power consumption.

The SPE collaborate better with the renewable sources of energy because they can operate with intermittent power. Unfortunately their total cost is higher because of the price of membrane and the high purity of water.

- Solid oxide electrolyte

The newest technology in water electrolysis is the solid oxide electrolyte cells (SOE). Their operation is based on high temperatures which can reach the 1000 (oC), where the water is formed as steam. Comparing to other electrolyzers, solid oxide electrolytes are requiring less energy in order to split the hydrogen from the water because of the water that has the form of steam. A typical SOE cell operates in range from 0,9 – 1,2 (V) at 800 (oC), but generally as much the temperature increases as the energy decreases.

In order to resist in high temperatures, the materials that are used have as base the ceramic. More precisely the SOE electrolyzers are using the solid ceramic electrolytes which provide also good ion conductivity. During the electrolysis, the hydrogen is formed in the cathode which has porous design kin order to allow the access to oxygen to pass and to be separate from hydrogen. In other words facilitates the movement of oxygen ions.

There are two types of SOE electrolyzers, the planar and the tubular design. In both types the electrolyzers are connected in series and the construction of the cell is similar to SPE cells. Planar design is advantaged over tubular design because it utilizes better the energy input. However, this technology is under development because of the high temperatures that restrict their operation.

4.2 Wind farms

4.2.1 Introduction

Wind farms are a promising way for sustainable massive production of electricity. The first wind farm constructed at the beginning of 1980 in California, in order to expand the energy market reducing at the same time the price of electricity. Today reports show that almost 100 gigawatts (GW) are installed of worldwide. It is also estimated that at the end of 2012 the installed capacity will reach 200 gigawatts (GW).

Wind farms consist of individual wind turbines suitable to take advantage the wind speeds but also the specificity of the surrounding area. The size of wind farm can be defined only from the installed capacity and from the number of wind turbines with other worlds is depending on the budget of the project, however a single turbine can't be considered as a "farm" while the larger wind farms are covering significant amounts of land or sea.

The design of wind farms require detailed study in order to take advantage the maximum energy from the wind but also to consider the various constrains, environmental and residential. The distribution of wind turbines inside the farm is a significant factor, considering the maximum installed capacity with the minimum losses.

Wind farms have quicker construction time, providing in short time electricity, while their operation could start after the construction of the vital parts of the wind farm such as the grid connection

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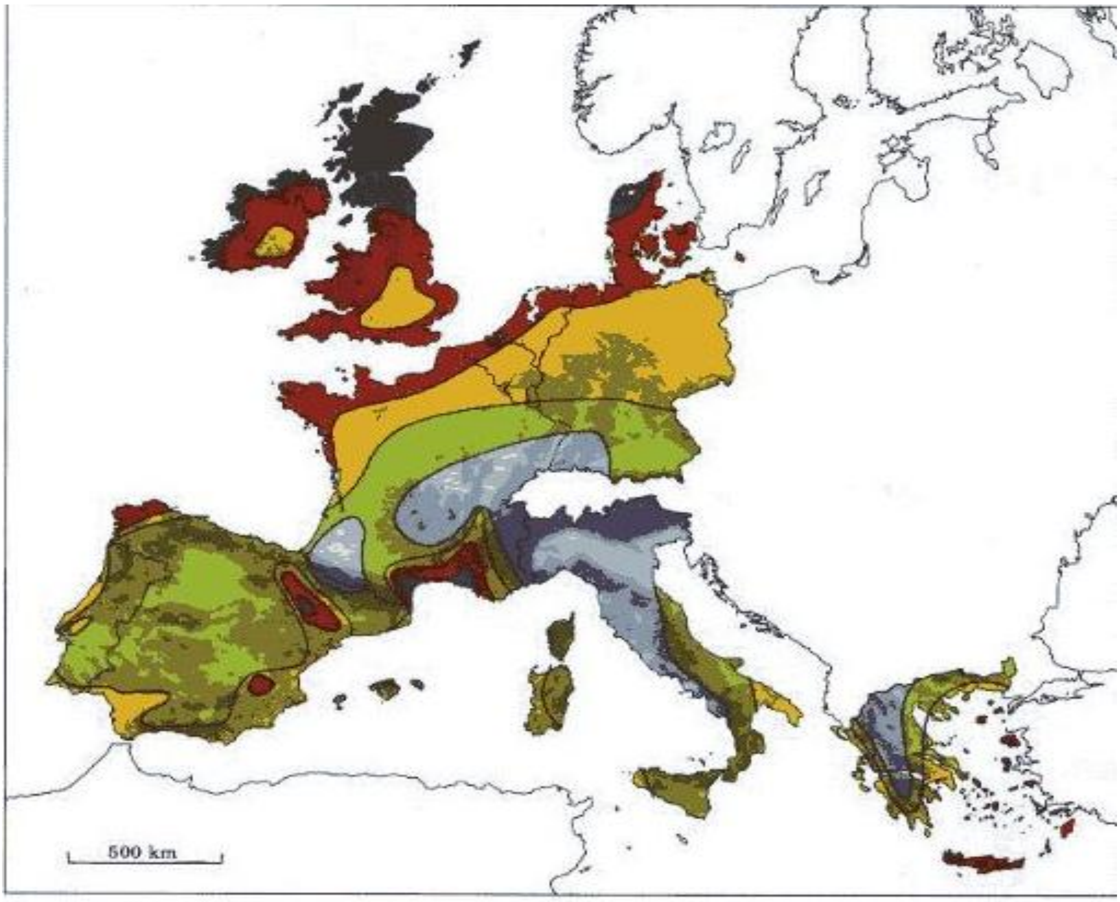
4.2.2 Locations of wind farms

The location of the wind farm needs long term planning, collecting at least 3 years detailed data of wind speed and wind directions for the better prediction of the annual viability and energy production.

Various tools have been developed in order to make easier the selection and the study of an area for wind farm installation. The wind map is a tool that shows the average wind speeds in various heights but also the average wind directions. Below map (figure 4.2) shows the potential average wind speed in the regions of Europe. Other maps are presenting even more detailed data such as the land usage and the transmission lines.



Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700

Figure 4.2 : Wind map [3]

Another useful tool is the below table (figure 4.3) which is devide the wind power in various classes. The table gives information for wind speed in relation to the wind density in various heights. Generally, is preferred the wind speeds to be greater than 4,5 (m/s).

Classes of Wind Power Density at 10 m and 50 m[a]				
	10 m (33 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Speed[b] m/s (mph)	Wind Power Density (W/m^2)	Speed[b] m/s (mph)
1	<100	<4.4 (9.8)	<200	<5.6 (12.5)
2	100 - 150	4.4 (9.8)/5.1 (11.5)	200 - 300	5.6 (12.5)/6.4 (14.3)
3	150 - 200	5.1 (11.5)/5.6 (12.5)	300 - 400	6.4 (14.3)/7.0 (15.7)
4	200 - 250	5.6 (12.5)/6.0 (13.4)	400 - 500	7.0 (15.7)/7.5 (16.8)
5	250 - 300	6.0 (13.4)/6.4 (14.3)	500 - 600	7.5 (16.8)/8.0 (17.9)
6	300 - 400	6.4 (14.3)/7.0 (15.7)	600 - 800	8.0 (17.9)/8.8 (19.7)
7	>400	>7.0 (15.7)	>800	>8.8 (19.7)

Figure 4.3 : Table of wind density [4]

The ideal location for wind farms is the area where the wind flow isn't turbulent and the power of wind increases gradually for the avoiding of damage the turbines. High objects of the surrounding area such as trees or hills are influencing negative the winds behavior.

Another problem that must be considered is the "wind park effect" which is caused from the interaction of wind speed and direction among the turbines as a result to disturbed the wind distribution. This problem is depending on the way that wind turbines are distributed in the wind farm.

The environmentalists supporting that wind farms are causing problems to bird life, while during the construction are disrupting the surrounding nature. However statistics have shown that bird deaths by wind farms are negligible compared other human activities.

Also significant issue is that the people who live close to wind farms have problem with the noise and the view impact of wind turbines, but again comparing to conventional power plants the environmental impact is the same while conventional power plants are causing health problems to the people.

4.2.3 Wind farms categories

- The onshore wind farms are installed in more than 3 kilometers from the nearest shoreline. The constructors are considering to take advantage the particularity of the surround area with the best accelerations of the wind. Today the countries with the biggest installed capacity form the onshore wind farms are covering more than the 10% of their needs.

- The near-shore wind farms is constructing in less than 3 kilometers of shoreline and 10 kilometers from shoreline inside the sea. Here the different temperatures during the day by the interaction of land and sea are affecting the wind speeds creating a continual movement.

- The offshore wind farms are located in more than 3 kilometers inside the sea in order to be exploiting the negligible resistance that finds the wind in the sea. It must be noticed that there isn't any visual impact and noise from the wind turbines. Furthermore, it is easier the transportation and the lifting of the wind turbines because of the power of buoyancy..

4.2.4 Components

The SCADA is a vital system for the wind farm operation which acts as the brain that collects and process all the information. The different information's are came from each wind turbine, from the meteorological stations and the substation. The system also is keeping a detailed data record such as the wind behavior and the energy production that are useful for the future operation of the farm.

The electrical system of a wind farm is a medium voltage network that varies between 10 (kV) and 35 (kV). The interconnection of wind turbines is preferred by underground cables instead overhead although their cost is higher. Due to the variety of different size of the wind turbines in the site are required transformers to stabilize the voltage in the same level. The total electricity is gathered to a central point named point of connection (POC) in order to be delivered.

The meteorological station usually is a tower with height for 30 to 60 meters that has installed various instruments such as anemometers and wind vanes in different heights of the tower in order to record the wind speed and the wind direction. Usually, this meteorological tower is expensive to be constructed in small wind farms.

4.3 Power stations

4.3.1 Introduction

The growth of power demand worldwide has forced many governments to invest at energy projects. The last years many combined cycle power plants (CCPP) have been constructed in order to cover their needs, while the size of a unit is relates with the energy requirement, the fuel availability and capital cost.

The total efficiency of a power plant relates by its thermodynamic cycle. The combination of more than one thermodynamic cycle in a single unit increases the performance. The combined cycle power plants are providing higher overall efficiency than the single steam turbines while the combustion engines ensure fuel flexibility.

The first thermodynamic cycle operates as the heart of the plant since it supply with heat the second cycle. Thus, the thermal losses are reduced from the first cycle while exploit from the second cycle.

More precisely, a combustion engine is generating electricity while the exhaust gases are moving to a boiler where water is heating. The water is turned into steam which in turn drives the steam turbines in order to produce more electricity. Below figure 4.4 is showing a simple diagram of a CCPP unit.

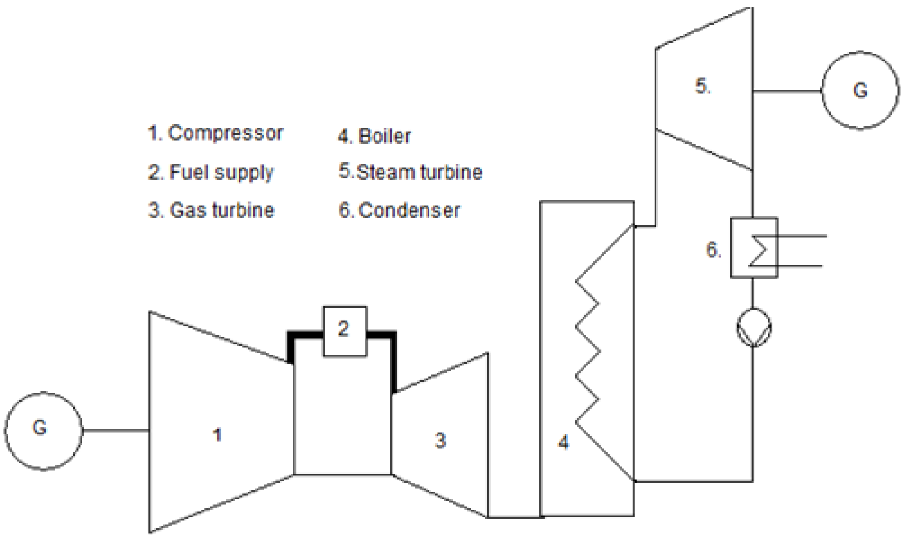


Figure 4.4: Diagram of a CCPP

4.3.2 Combined cycle power plants

The Combined cycle power plants usually consist of one or more gas turbines with the corresponding heat recovery system generation and the steam turbine. It is preferred in the CCPP to include gas turbines over piston engines because of the higher efficiency they offer.

The temperature inside the gas turbine reaches the 1200 (°C) while the temperature of the exhaust gases at the input of the boiler is around 650 (°C). The overall efficiency of the system can reach 55 (%). The materials are used must have good resistance to high temperatures, thus are preferred alloy metals for high temperatures.

The working fluid that is used in most power plants is water and for this reason power plants are constructed near to the sea or near to lakes. The plants constructed near to sea require having demineralization unit in order to avoid the corrosion from the salt, while the material must have salt resistance, such as stainless steel or aluminum.

The maximum power output of a combined cycle power plant is depending on the size of the gas turbines of the first cycle and from the size of the steam turbine of the second cycle. Most CCPP have more than one gas turbine in the first cycle in order to maximize the electricity production and to support a maximum capacity of a steam turbine.

Sometimes the temperature of the heat recovery steam generation system needs to be raised in order to be attained the maximum electrical load, thus a supplementary firing system is added. The extra system usually is installed as a backup for mechanical problems of the gas turbines but also to cover the hours of the maximum demand, however when is used is decreases the overall efficiency of the power plant.

The combined cycle power plants use various types of fuels in liquid or gaseous form and sustainable fuels reducing significantly the environmental impact. The new types of combine cycle power plants have also integrated solar panels taking advantage the power of sunlight to heat the water for the heat recovery steam generation system or to produce steam for other procedures.

4.3.3 Integrated solar combined power plants

Integrated solar combined cycle power plant is a new technology that combines the benefits of a solar energy system with the benefits of a convectional power plant in order to reduce the emissions and to increase the efficiency. The philosophy of this technology is based the knowledge on consecrating solar power (CSP) where solar collectors transform the sun energy into heat in order to produce electricity.

The operation of the combined cycle power plants is remain the same having as the only difference that the solar collectors are adding significant amounts of heat power to the heat recovery steam generator (HRSG) by reducing the fossil fuel consumption and increasing the power production at peak hours with very low cost.

The difference between CSP and ISCC is that the second technology is more reliable since it is a continuous power source. Although, the ISCC power plants can reduce significantly the CO2 emissions and fuel consumption, it can't be regarded as a mean of climate change restriction.

The size of a CSP installation starts from few kilowatts (kW) whereas the ISCC depends on the sizes of a gas and steam turbine, the fact is that CSP systems can double the size of a steam turbine of a CCPP plant. The cost difference of a standalone CCPP over an ISCC is small since the kilowatt per hour costs about 0.05 €. Thus, all the existed conventional power plants can change to ISCC if their location is in sunlight areas and if it is available the required space for the solar field.

Below figure 4.5 is a diagram showing the two different systems of the ISCC power plant.

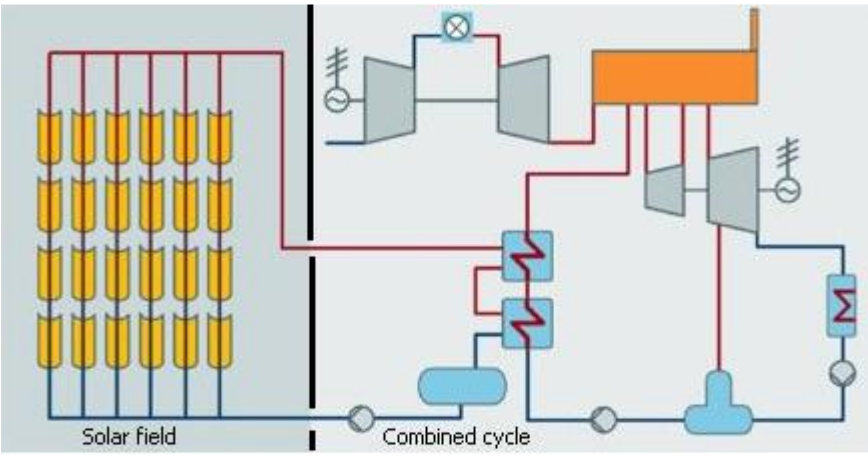


Figure 4.5: Diagram of an ISCC

Today the most investments in ISCC power plants have been made in countries with abundant sun light in region of South Europe, North Africa and Meddle East. The topography is very important because the solar panels operate with direct normal radiation, so the higher radiation the higher efficiency. Obviously, the maximum efficiency on ISCC systems is the day where those regions have higher loads from cooling systems.

4.3.4 Gas turbines and hydrogen combustion

The advantages of gas turbines over other combustion engines are the reason that many manufactures prefer to include it in large scale combined power plants. Last decades new types of gas turbines have been manufactured in order to combust hydrogen while new types of power plants have been invented.

Also several studies have shown that natural gas is preferred as the most cost effective fuel and hydrogen as the most reliable fuel to reduce the CO_2 emissions. Below figure 4.5 from a GE study indicates that gas turbines have a big range of fuel flexibility while hydrogen is the most efficient.

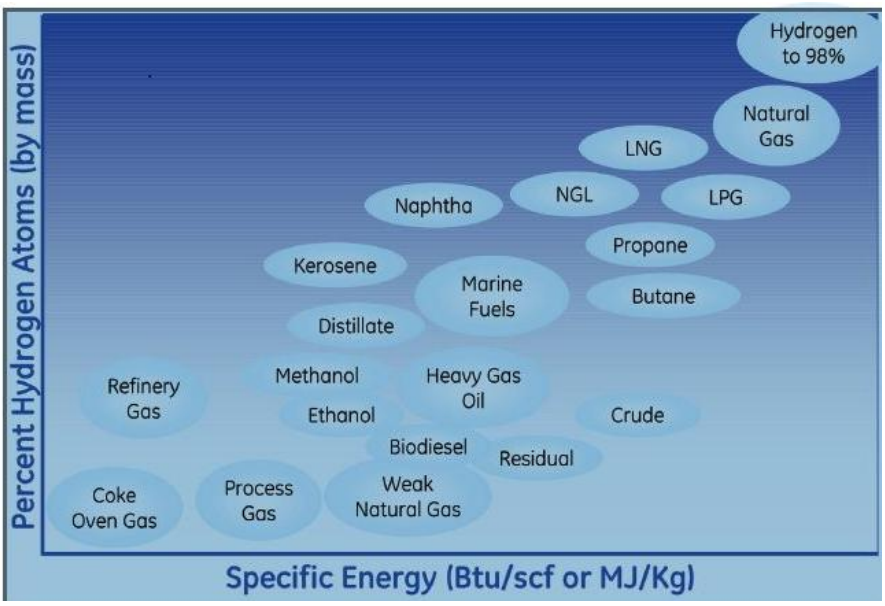


Figure 4.6: Gas turbine fuel flexibility

Integrated gasification combined cycle (IGCC) and integrated reformer combined cycle (IRCC) are two types of power plant that combust hydrogen or hydrogen-based fuels (syngases). To date, their operation in relation with hydrogen combustion proved very safe and their equipment reliable over time.

The IGCC and IRCC plants contain an integrated refinery or gasification unit that elaborates conventional fuels, as coal and natural gas, extracting the hydrogen and supplies it directly for combustion. Below figure 4.6 shows a simple unit of integrated gasification combined cycle power plant.

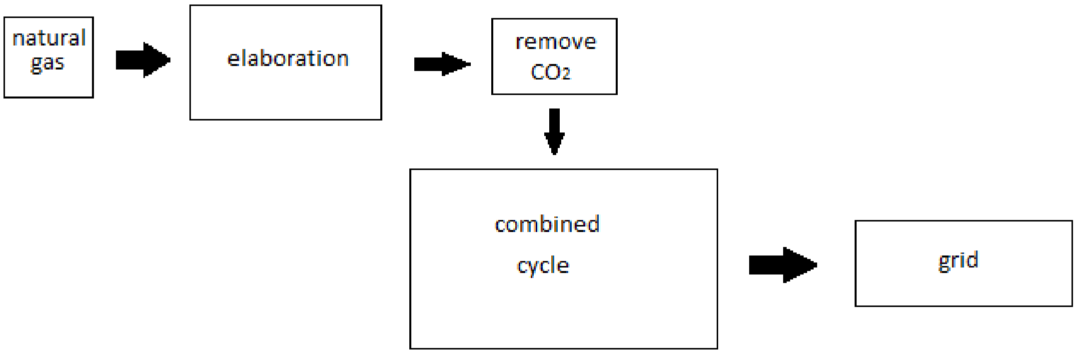


Figure 4.7: Diagram of a IGCC

The combustion of net hydrogen requires the usage of different material of the gas turbine equipment because of the high firing temperatures. For practical reasons, mostly economics, in order to reduce the cost of the materials, most manufactures are diluent the hydrogen with nitrogen or steam (syngases).

The desire level of dilution is when the firing temperature of the syngas is equal to natural gas firing temperature. Usually, hydrogen works in the syngas in proportion up to 90% in volume. Furthermore, this facilitates the fuel flexibility since a natural gas power plant can be equipped to run also with syngas.

Nevertheless the combustion of nitrogen releases in the atmosphere NO_x emissions. NO_x control is required because the emitted gases are responsible for the ozone hole and also for the acid rain in the industrial areas. Thus, techniques similar to those of CO2 reduction are used with success.

5. Project profile

5.1 Introduction

The island of Cyprus is the 3rd bigger island in the east Mediterranean Sea and it lies at the crossroads of three continents (Asia, Africa and Europe). The island is divided into two nations. However, this case study takes place in the Greek Cypriot area in which corresponds the 60% of the land. The total population had recorded in 2009 about 800.000 residents while in the capital city Nicosia lives almost the half population. According to estimations of Eurostat the population of this area at the year 2035 will be near to 1.5 million people.

With the growth of population, the power demand is expected to grow as well, resulting in the need of constructing new power production units. Unfortunately, Cyprus doesn't have its own production of fuel energy resources, so it depends on other countries for its supply. This results in spending significant amount of money to import fuel while at the same time Cyprus has plenty renewable sources of energy.

Today, the majority of the power stations in Cyprus are operating with oil and coal while the natural gas is expected to arrive to the island in the near future. In spite of the low cost of oil and coal the cost of the imported fuel is significantly high considering the fact that the installed power capacity is approximately 1500 (MW). Furthermore, the exclusivity in the use of fossil fuels is aggravating the pollution in global scale by the exhaust CO_2 emissions.

Having advantage in renewable energy sources, Cyprus can significantly reduce the amounts of the conventional power plants energy production while at the same time can contribute to the commitments of the CO_2 emission reductions. Moreover renewable energy sources are a great investment in the further expansion of power production.

In Cyprus blow strong winds all over the year due to its long distance from the overland areas and the big climate difference that exist over the island; hot southern weather and cold winds of the northern mountains of Asia. The average daily sunshine is 12.5 hours and the number of the sunshine days is approximately 300 per year. This is a great advantage for the investment in solar energy projects.

However, Cyprus hasn't invested in large scale renewable energy projects such as wind farms and photovoltaic parks. Though, being a European Union member charges Cyprus with the obligation to reduce CO_2 emissions. Written in numbers, Cyprus must produce the 13% of its energy from renewable sources until 2012.

Over the last years there has been a fast growth in the construction section. New buildings are built all over the island as a result of the tourist industry development. However, every summer many problems occur as far as the power supply is concerned. The government in order to deal with the problem invested in the construction of the biggest power plant of the island that will supply the country with the 70% of the total energy. Unfortunately, the fast growth requires more investments in the power production and taking into account the CO_2 reduction commitments there is no other way but the future energy investment to be in the renewable sources.

The project investigates the advantages and the solutions of this option in order to make the existing combined cycle power plants sustainable. The concept is to integrate a wind-hydrogen system in a simple model of a combined cycle power plant. The produced energy from the wind farm will be converted into hydrogen through water electrolysis in order to supply the gas turbine.

The case study also deals with the specificity of the surrounding area of the existing power plant and is proposing an alternative plan to the governmental one. The below map (figure 5.1), shows the location of the wind farm (the highlighted red area), which has been proposed by the Cyprus Government for the construction of an energy center that will store and process the imported fossil fuels.

Figure 5.1: Panoramic Photograph of the Vasilikos area.

The area is in “Vasilikos” region and it covers approximately 2.3 km^2 of a barren and polluted land. It is an industrial region that consists of the power plant, an old chemical industry and a quarry that has stopped working for many years. However, the surrounding area is residential, inhabited by farmers and fishers who use the land for agriculture and the sea gulf for fish hatcheries. Furthermore, studies have shown that the area already suffers from chemical and radiological pollution and the future plans of the government will aggravate further the area.

5.2 *Wind farm*

The data have been collected from the wider area of the county of Larnaka where Vasilikos power station is located. At the same coastline and west of the power plant, in a distance of approximately 25 km is the airport where the meteorological station is installed. The wind climate data that are used for the simulation program are the statistics of a nine year period which records the wind speed from 7 a.m. until 7 p.m. local time at 10 meter height [5].

In order to carry out the results of the wind turbines power production a simulation program has been used in which the wind data and the technical characteristics of the wind turbine are applied. The results from the simulation program can be extracted in yearly, monthly and hourly scheme.

As it has been mentioned before, a meteorological station should be installed to the wind farm, in order to evaluate and to utilize the wind data with very high accuracy. The "met towers" is a simple construction of a metal column which is supported to the ground by wires. The tower usually has the same height as the wind turbines and at the top of the column an anemometer and a direction vane are installed. The cost of a typical met station of 50 meter height varies between 2.700 € and 8.000 €. [6]

The graph below (Figure 5.2) indicates the average monthly wind speed from the recorded statistics, while the annual average wind speed is 5.123m/s. However, the wind speed varies with the different hub heights and the graph (Figure 5.3) shows the wind speed profile of the wind turbine for the different heights.

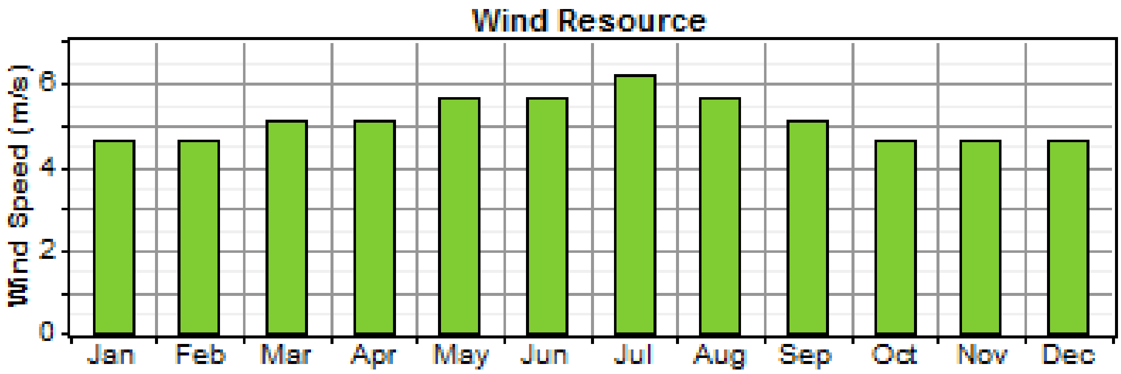


Figure 5.2: Graph of average monthly wind speed

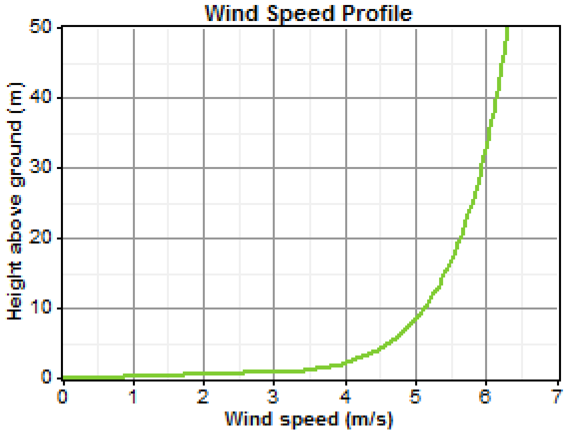


Figure 5.3: Graph of wind speed distribution in relation with height

Also, in the table below (figure 5.4) appear some advantaged parameters of the wind speed that are taken into consideration for the evaluation of the power production.

Weibull k	2
Autocorrelation factor	0.85
Diurnal pattern strength	0.25
Hours of peak wind speed	15

Figure 5.4: Table of wind speed parameters

- The weibull k is a number without units and characterizes the distribution of the wind speed over time. The graph below (5.2.2) shows different weibull distributions all with the average wind speed that we have.

- The autocorrelation factor is a number that indicates the strength of the wind within an hour compared to the strength of the wind in previous hours. The number is related to the complexity of the region that the measurements have been made and a normal values ranges between 0.80 – 0.95.

- The diurnal pattern strength is the reflection of the strength that wind speed has on the time of day. In normal situations of the value vary between 0.0 – 0.4.

- The value of hour of peak wind speed indicates the average windiest hour of the day.

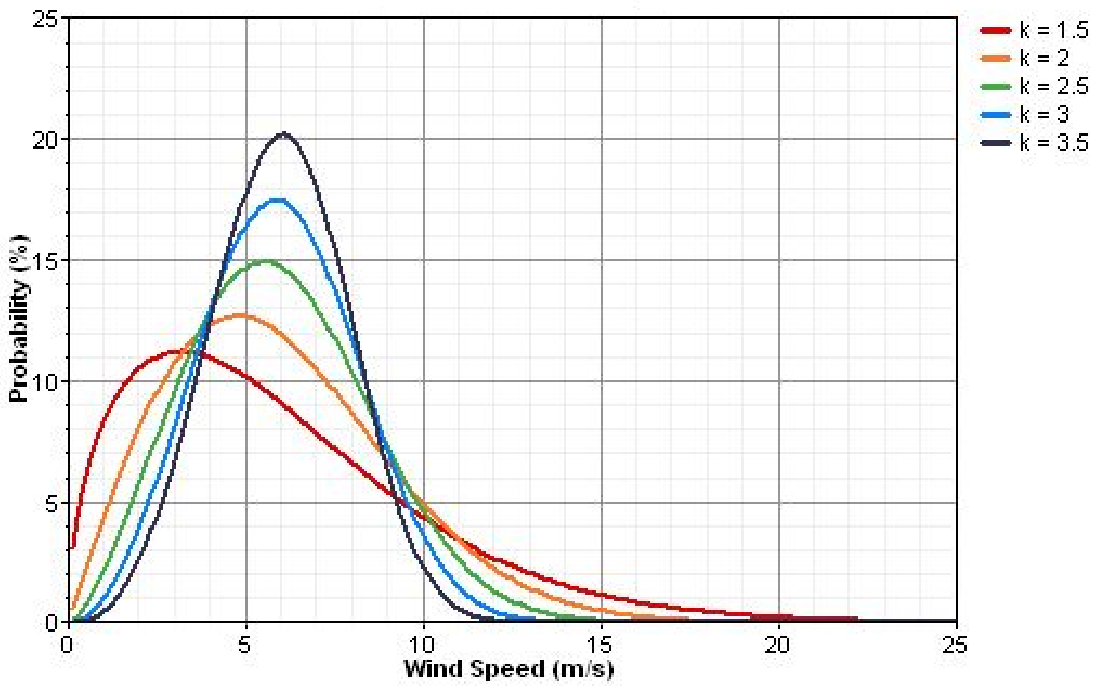


Figure 5.5: Graph of weibull distribution

The wind turbine is the E44 model of Enercon which is a three blade and it has 900 (kW) rated power. The figure below shows the wind turbine while beside are the technical characteristics of the model. The height of the wind turbine is bigger than the height of the anemometer so the wind speed needs to be scaled up in order to to correspond of the actual wind turbine height.

- Rotor diameter = 44 (m)
- Hub height = 45(m)/55(m)
- Wind class = IEC/NVNIA
- Turbine concept = Gearless, variable speed, variable pitch control
- Rotor type = Upwind rotor with active pitch control
- Swept area = 1,521 (m^2)
- Blade material = Fiberglass (epoxy resin); integrated lightning protection
- Rotational speed = 12 - 34 (rpm)[7]

Figure 5.6: Image of E 44

The graph (Figure 5.6) indicates that for a 45m height the wind speed is (6,2 m/s) while a single wind turbine has an annual power production of 1,638,280 (kWh).

5.3 Hydrogen system

The hydrogen generation system consists of an alkaline electrolyzer, a compressor and a storage tank. These are the critical parts of a hydrogen generation system and a more brief analysis of them will be made below. Though, in order for the system to operate more safe and reliable, the use of an additional part is required, such as the control system.

The simulation program reformed the data from the wind turbines electricity generation and the technical characteristics of the electrolyzers, such as the capacity and the efficiency, creating the monthly, yearly and hourly profiles of the hydrogen production data. The electrolyzers are installed onsite creating a significant advantage since the production of hydrogen is cheaper with no transportation fees and direct fuel consumption. This project is highlighting the benefits of this procedure since the wind farm is located near to the power plant corresponding to the challenges for cost reduction.

The alkaline electrolyzer is from the Hydrogenics Company (7). The model is the HySTAT 60 and produces 24 - 60 Nm^3 per hour of hydrogen with purity of 99.9%. For the electrolysis is used a solution of water mixed with 30% of potassium hydroxide (KOH) which produce hydrogen at 10 bar pressure. The figure below (5.7) shows a picture of the model

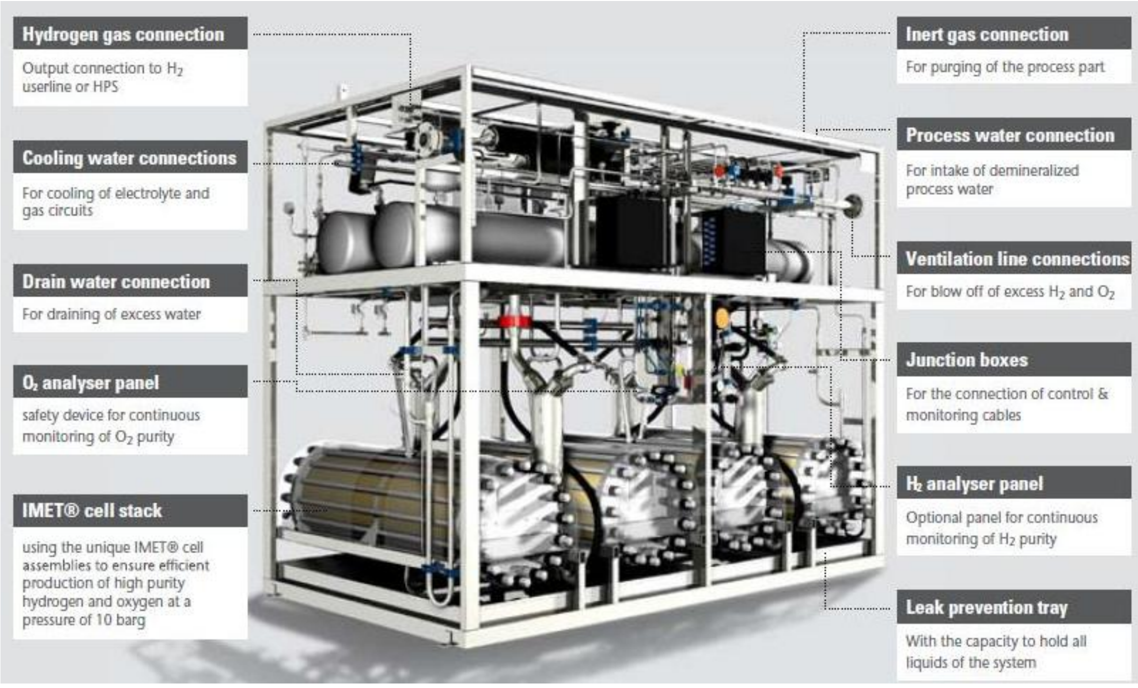


Figure 5.7: Alkaline electrolyzer with components [8]

There are two choices for the installation of the electrolyzers, either the electrolyzers will be established close to the wind turbine site or all together on a well-established place.

The hydrogen gas before its storage needs to be compressed in high pressure. The hydrogen compressors are working at pressure from 5 (bar) to 1000 (bar). The industrial applications require high pressure while the production of hydrogen by water electrolysis is made in very low pressure. Moreover the compression reduces the required space that hydrogen gas takes up in the tank.

The compressor is a multistage machine, from the Hydron-Pac inc, which receive from the electrolyzer gas with pressure from 2 to 10 (bar) and send it to the tank with 400 (bar) pressure. The figure below (5.8) shows the machine that starts the operation automatically through the electronic system whenever the electrolyzer starts producing hydrogen.

Figure 5.8: Hydrogen Compressor [9]

The hydrogen storage tank is a steel high pressure vessel, from CP industries, that holds the fuel in the form of compressed gas. In order to increase the capacity storage many vessels can be connected together creating a set. The maximum storage capacity of a vessel is 69 kg of hydrogen with inlet pressure up to 10 (bar) and maximum pressure up to 240 (bar) in 30 (^{o}C). Figure 5.9 shows the high pressure storage tank.

Figure 5.9: High pressure storage tank [10]

5.4 Gas turbine

The SGT-100 gas turbine is a Siemens model with a power out-put ranging of 5.4 (MW). It can be used for a combined cycle applications. It is consuming various types of gaseous and liquid fuels while combination of fuels is available. The electrical efficiency is 31% rating with a heat rate of 11,613 (kJ/kWh). The exhaust gas flow is 20.6 kg/s, at 531 (° C) temperatures [11].

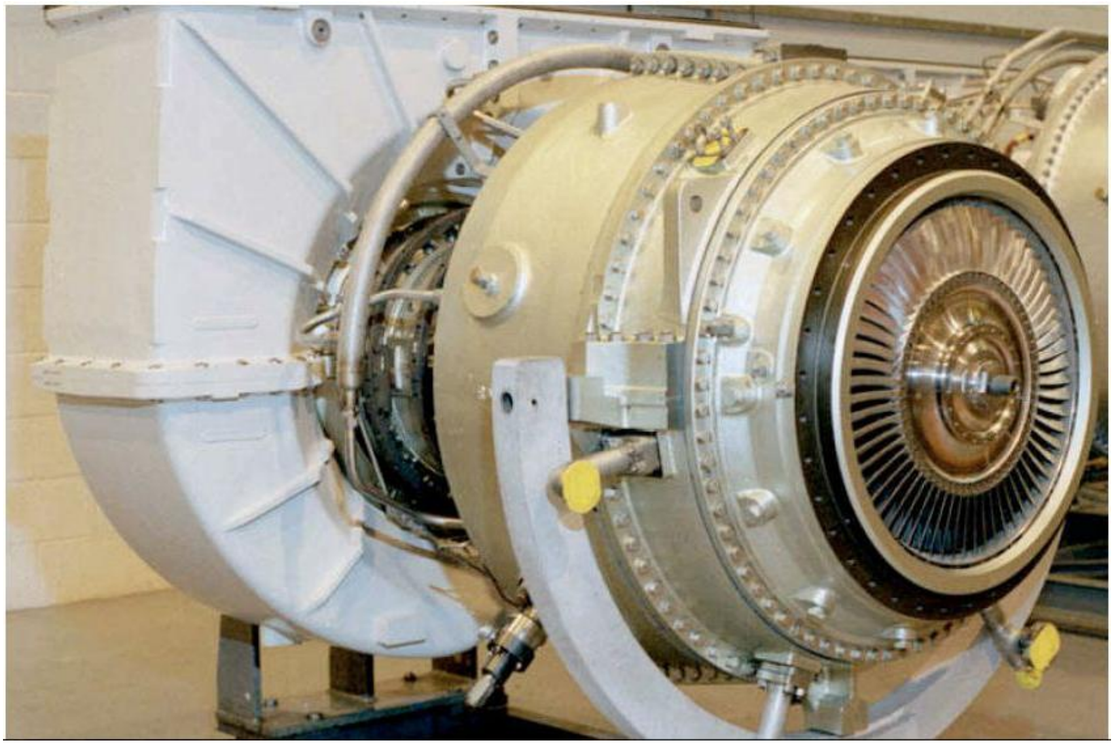


Figure 5.10: Siemens Gas turbine [11]

6. Result and analysis

6.1 Introduction

The project results were performed with Homer simulation program and Microsoft Excel in order to extract the results in an hourly basis format. Homer simulation program gives the opportunity to optimize the wind-hydrogen system in correlation with the needs of gas turbine for fuel consumption and calculates the electricity output and hydrogen production. For example, it “designs” the best scheme for the wind-hydrogen system in order to meet the needs of the gas turbine for hydrogen, taking also into account some parameters for the estimation of the payback time.

The simulations require entering the systems characteristics such as the technical parameters, the system’s capital cost and the climate data. Thereafter it processes the information creating different system schemes according to the cost of installation and operation. The figure below shows the model system components.

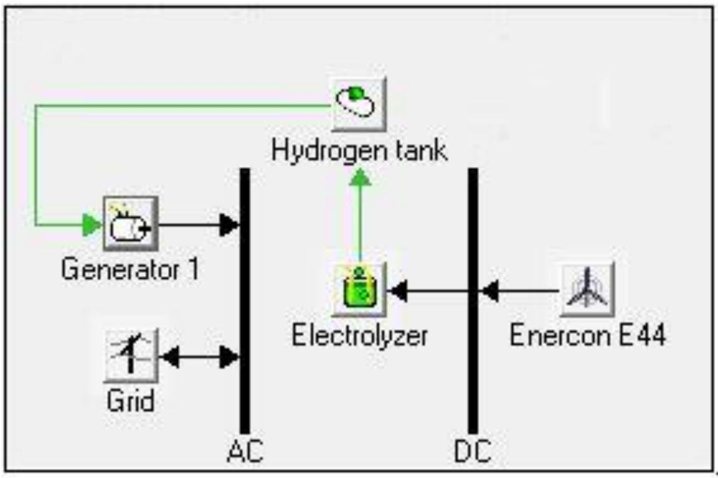


Figure 6.1: System components

The purpose of the simulations is to create a single profile of the system that will cover the needs of a small power plant and then make some hypothetic scenarios in order to investigate the best scheme that provides viability of the system, fuel independence and environmental sustainability.

6.2 Gas turbine results

The maximum gas turbine capacity is 5.4 (MW), however the gas turbines can rarely operate at maximum power. In most cases power plants operate at the 60 up to 80 (%) percentage of their maximum power in order to achieve smooth operation and good efficiency. Less than 50% reduces the efficiency of the power plant since the exhaust gases can't support the heat recovery system.

The simulations where made considering that the gas turbine is operating in the 80 % of its maximum power for the summer months, where is the maximum electricity demand in Cyprus, while for the rest of the year the simulations made with the gas turbine operating in 60% power. The gas turbine yearly electricity production is 9,132,300 (kWh/yr), which is corresponding approximately to 2000 houses when the average yearly electricity consumption of a household is 5000 (kWh)[12].

Calculating the gas turbine fuel consumption:

The efficiency of the gas turbine is 31.4 (%) percent. In 1 (kWh) kilowatt hour is 3414 (Btu) the fuel consumption is:

$$\frac{3414}{0.31} = 11012 \left(\frac{Btu}{kWh}\right)$$

The low heating value of the hydrogen is 113077 (Btu/kg), so the hydrogen consumption in the gas turbine is:

$$\frac{11012}{113077} = 0.095 \left(\frac{kg}{kwh}\right)$$

The corresponding consumption for the most common fuel is: for natural gas 0.21 (kg/kWh) and for diesel 0.26 (kg/kWh). As we can see, the fuel consumption of natural gas is double than that of hydrogen per kWh. The low heating value of hydrogen is approximately higher than other fuels, therefore same efficiency engines require less fuel when combust hydrogen.

In the table[13] below we can see the properties of the most common fuels that gas turbines combust. The data table with the fuel properties has been entered in homer program for the calculation of gas emissions and the fuel consumption of the gas turbine.

(kg/yr)	*Diesel*	*Natural gas*	*Hydrogen*
Low Heating Values (Btu/lb)	*18,397*	*20,267*	*51,682*
Density (kg/m^3)	*820*	*0.79*	*0.09*
Carbon content (%)	*88*	*67*	*0*
Sulfur content (%)	*0.33*	*0.33*	*0*

Figure 6.2: Fuels properties

The yearly fuel consumption of hydrogen is estimated in 305,200 (kg/yr), however, as referred in chapter 3, the gas turbines consume hydrogen diluted with nitrogen or steam in order to reduce the combustion temperature avoiding this way the problems made to the gas turbine materials.

For the project we consider that the dilution with steam presents higher environmental sustainability since there are no nitrogen emissions (NOx). The fuel is usually diluted in steam rate from 10 to 20%. The following table shows the annual operating data of the gas turbine.

	Hours of operation (hr/yr)	*Capacity factor (%)*	*Electrical production (kWh/yr)*	*Fuel consumption (kg/yr)*
Turbine operation	*8,760*	*30.0*	*9,132,300*	*305,200*

Figure 6.3: Gas turbine annual data

Considering that during the summer months the Cyprus has the maximum electricity demands, the gas turbine is set to operate in 80% rating. In below graph is shown the monthly average electric production in kilowatts. More precisely the monthly average electric production for each summer month is 1,290 (kW), while for the rest months 960 (kW).

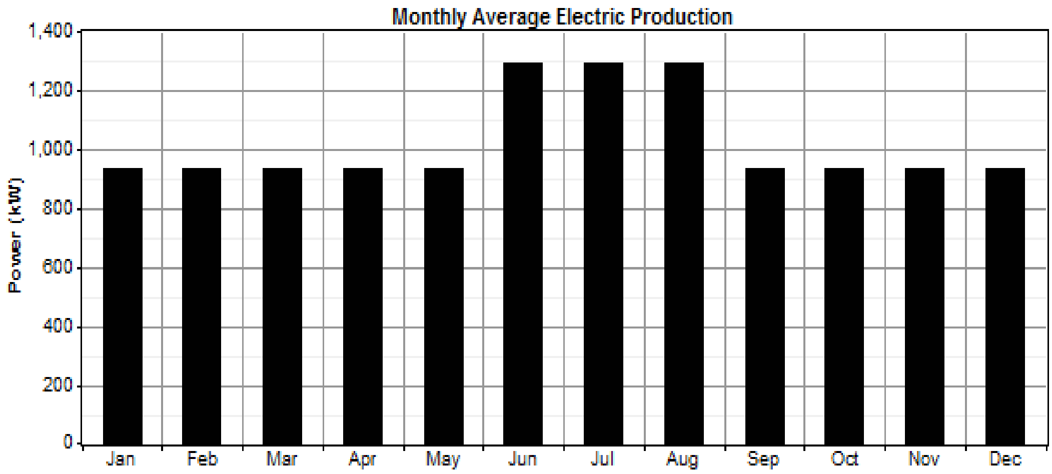


Figure 6.3: Gas turbine monthly average electric production

Gas turbine emissions:

The most important purpose of this project is to highlight the benefits of the hydrogen combustion in limiting the problems caused in the environment by the conventional fuel combustion. The table below shows the annual fuel emissions from the gas turbine. The table contains the most harmful exhaust gases by-products form diesel and natural gas combustion.

(kg/yr)	*Diesel*	*Natural gas*	*Hydrogen*
Carbon dioxide	*10,339,047*	*5,173,234*	*0*
Carbon monoxide	*47,659*	*32,769*	*0*
Nitrogen oxides	*406,247*	*288,364*	*0*

Figure 6.3: Gas turbine emissions

6.2.1 *Wind-hydrogen results*

The wind farm provides with DC current the electrolyzer which is regulated to operate only when the wind blows. As more wind turbines operates the more the capacity factor increases, reducing at the same time the cost of production.

The simulations have shown that the wind farm should be consisted by 7 wind turbines with total capacity of 6300 (kW) and electrolyzers with total capacity 3500 (kW) producing 300,232 (kg/yr) of hydrogen. In order to produce 1 (kg) of hydrogen is required 22 (kWh) of energy.

The graphs below show the monthly average electric production from the wind turbines. July is the month that the maximum energy (3400 kW) is produced which is also the amount of energy that must be consumed by the electrolyzers. The electrolyzers' capacity depends on this number.

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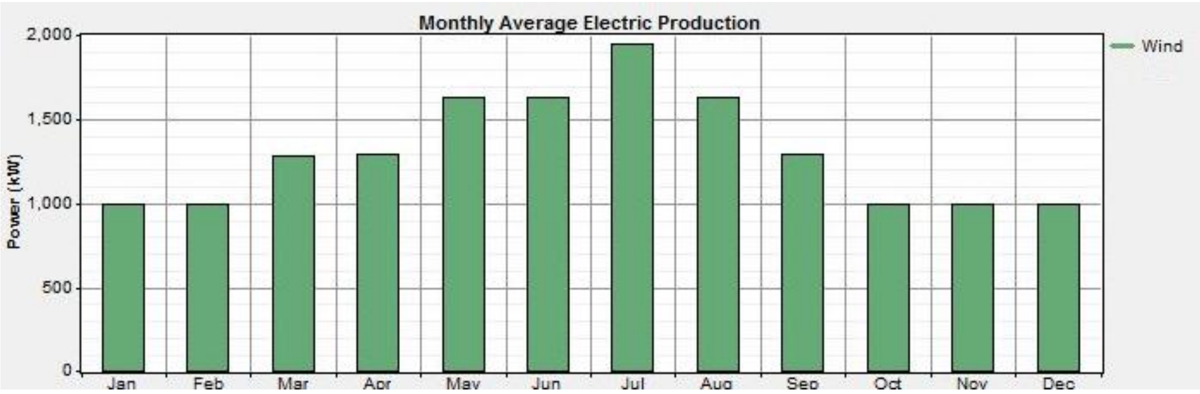

Figure 6.4: Monthly average wind farm electricity production

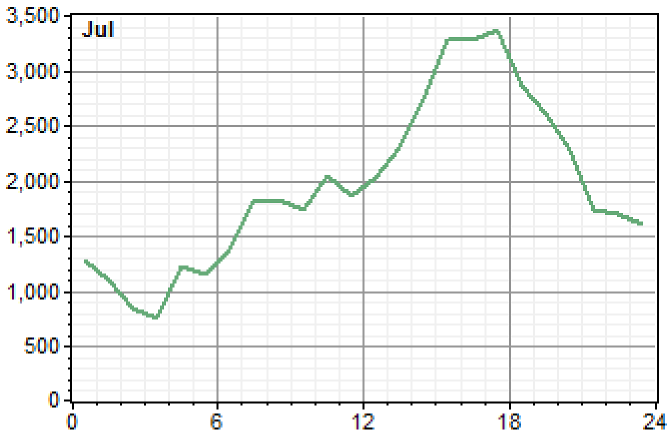

Figure 6.5: Maximum wind farm electricity production

In the case study, the wind farms site is near the gas turbine location, having an average wind speed 5.12 m/s. The wind-hydrogen system is synchronized to operate only when wind is blowing and the wind farms produce energy for the electrolyzer.

The table below shows details of the wind farm. It is interesting to note that although the average wind speed is in low levels the total hours of production show that almost all year long the wind turbines are operating. The cut-in power of the turbines is 2 (m/s) while the cut-out 25 (m/s).

Total power production	*Total hours of production*	*Capacity factor*	*Mean output*	*Maximum output*
6,533,120 kWh/yr	*8580 hr/yr*	*20.8*	*1,870 kW*	*9,100 kW*

Figure 6.6: Wind farm annual data

More analytical in the graph below is shown the hourly data of the year for the wind farm. The collored areas represent the power produced each hour per year while the black areas are the period without wind.

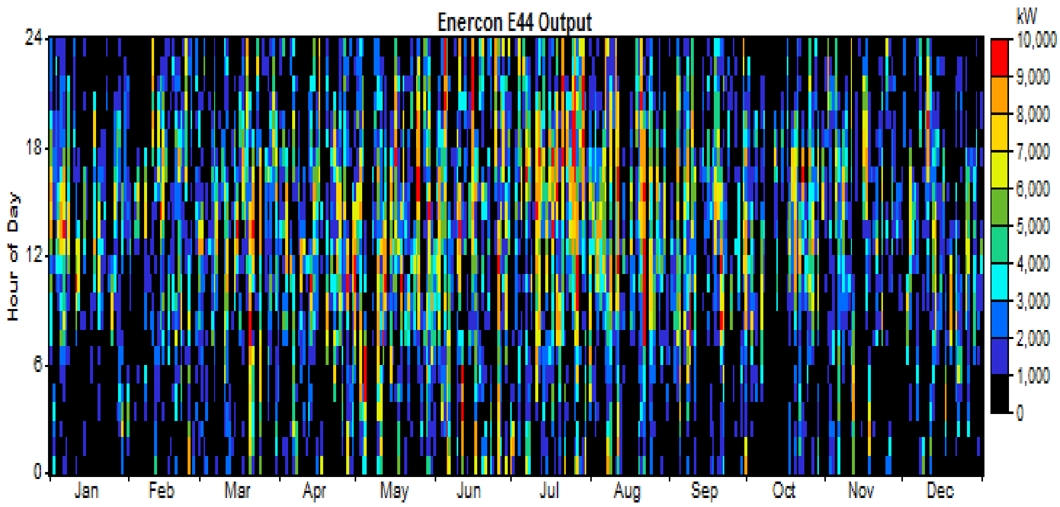

Figure 6.7: Wind farms annual hourly data

One of the most difficult things is to produce hydrogen in a cost that is competitive to natural gas and oil process. In order to be even more competitive hydrogen must be produced from clean sources such as renewable sources.

The simulation showed that the electrolyzer should have total capacity of 3400 (kW) meaning that for each wind turbine corresponds an electolyzer of 500 (kW). The electrolyzers receive DC current from the wind turbines. The graph below shows the average monthly hydrogen production in kilogram per day.

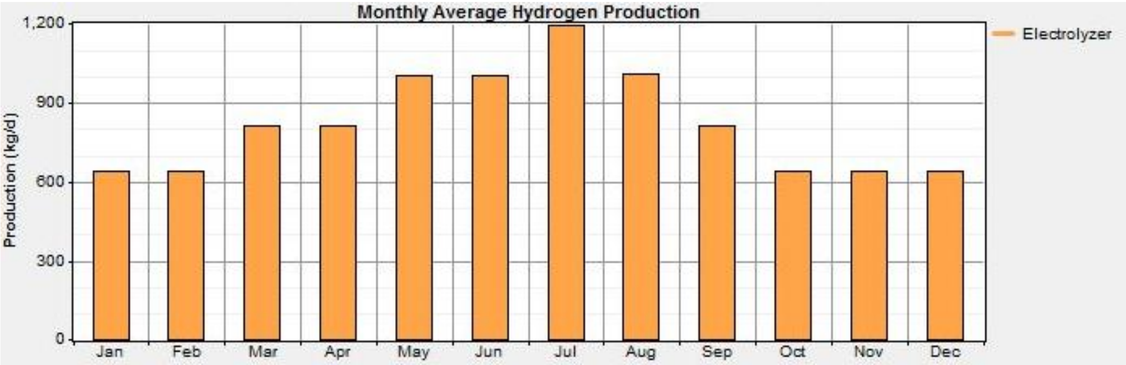

Figure 6.8: Monthly average hydrogen production

As we can see the maximum storage capacity reaches the 1200 kg per day. Because the daily consumption of the gas turbine is 418.082 kg, a storage tank of 1200 kg can store the double quantity of hydrogen for safety reasons.

6.3 Solar power results

The integration of a solar field is an optional system. It only operates during the day and it is useful for two main reasons in a power plant. It can reinforce the exhaust gases of the gas turbine that heat the water in the heat recovery steam generation system or support the operation of an auxiliary boiler that is required in order to keep in a steady temperature the start up of the CCPP.

Cyprus is a country with more than 300 sunny days per year. The average daily radiation reaches the 4 kWh/m^2 with 9.8 hours in December and 14.5 hours in June. It is assumed in the project that the solar field covers the daily needs of the steams turbine auxiliary boiler. The steam turbine usually has as maximum capacity the half capacity of the gas turbine. In our case study the steam turbine has 2 (MW) maximum power and maximum electricity out-put 5,256,000 (kWh/year).

For the project results it was used an Excel sheet, in order to develop the size of the solar field and to calculate the daily heat generation. For the calculation of the heat generation we need to know the daily direct radiation. The table below shows the monthly average daily direct radiation.

Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Annual*
1.042	*1.852*	*3.233*	*5.468*	*7.498*	*7.563*	*9.006*	*7.236*	*4.148*	*2.395*	*1.117*	*0.847*	*4.370*

Figure 6.9: Monthly average daily direct radiation

The amount of water that is required to feed the auxiliary boiler is approximately 1000 liter per hour in 190 (°C) in normal conditions. However depending on the pressure we can vaporize the water in lower temperature rates. The required energy is found from this formula:

Required Energy = (specific heat of water) x (mass of water) x (temperature)

Thus, the average monthly energy for the boiler is 80,000 (kWh) and is produced from solar panels with total surface of 600 (m^2). The table below shows the average monthly production in kWh.

Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
19,246	*29,673*	*56,277*	*74,661*	*94,667*	*119,918*	*114,770*	*98,881*	*67,216*	*44,239*	*19,023*	*15,764*

Figure 6.9: Average monthly heat recovery production

As we can see in order to cover the winter daily needs bigger solar panel surface is required. However, from April to September the daily auxiliary boilers' operation is totally covered.

A number of equations have been used in Microsoft excel in order to complete the above table:

1. declination (δ)

$$\delta = \delta_0 \times \sin\left[\frac{360 \times (284 + n)}{365}\right]$$

2. correction E

$$B = \frac{360 \times (n - 81)}{365}]$$

$$E = 9.87 \sin(2B) - 7.35\ cosB - 1.5\ sinB$$

3. hour angle (h)

$$t_{sol} = t_{ref} + \frac{4(L_{ref} - L) + E}{60}]$$

$$h = 15 \times [t_{sol} - 12]am$$

4. elevation (β)

$$\beta = sin^{-1}(cosl \times cosh \times cos\delta + sinl \times sin\delta)$$

5. Solar azimuth (γ_ς)

$$\gamma_\varsigma = cos^{-1} \frac{(sinl \times cosh \times cos\delta - cosl \times sin\delta)}{cos\beta}]$$

6. Direct solar on surface ($I_{b\Phi}$)

$$I_{b\Phi} = I_b(cos\beta \times cos\alpha \times cos\Phi + sin\beta \times sin\Phi)$$

And the final equation that gives the total heat recovered in (kWh):

$$= [I_{b\Phi} \times \alpha \times (abs.coeff) \times (trans.coeff)] - [(U\ val.) \times \alpha \times 40]$$

Where, (α) is the solar panel surface, abs. coefficient (0.95), the trans. coefficient (0.92) and U-value (1.1). These characteristics are the same for a common solar panel.

6.4 Economic analysis

The economic analysis approaches the overall capital cost of the system without including the cost of the radial components such as pipe lines or electricity cables. Similar project are not exist in the market in order to compare the capital cost.

The price of the combine cycle power plant is based on the project of "Vasilikos power station" [14]. Rototech Company gave important pieces of information for the capital cost of the CCPP. The table below shows the cost of each system.

Component	*Size*	*Capital (€)*	*O&M (€)*	*Years*	*Total cost (€)*
CCPP	*7,4 (MW)*	*1,023,600*	*26,821*	*20*	*3,050,058*
Wind-Hydrogen system	*6,3(MW)*	*4,707,948*	*70,156*	*20*	*8,613,268*
Solar system	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
Overall cost					*11,663,326*

Figure 6.10: power plants component cost

As we can see the wind-hydrogen systems capital cost is bigger than the cost of the CCPP which makes it a forbidden project. For a more cost-competitive system, it is more viable to change the location of the wind farm. Greater average wind speed enable better penetration of the wind farms electricity production, meaning that the same system will require less wind turbines to produce the same amount of hydrogen.

The cost of electricity in Cyprus is 0,144 (€/kWh), so the power plants payback time will be after 8 years of operation. A CCPP that uses natural gas has payback time approximately 2 years.

7. Conclusions

The case study is Cyprus shows that the wind-hydrogen system can be a reliable source for continuously fuel supply to the gas turbine. Nevertheless it performs better for even higher wind speeds. This fact makes solar energy power more attractive and lucrative for future investments.

The power plant can supply with continuous electricity a specific number of households which no other renewable source can provide. Theoretically, the wind farm can supply the same amount of energy but the intermittent operation discourages such kind of investments as a primer production source.

The conversion of wind turbines electricity to hydrogen is capable of creating the same constant production that a power plant does, but having also the most important advantage that of the zero CO_2 emissions. So these systems can be established as the ideal solution for small communities, for example one of 2000 households.

Seven wind turbines and the corresponding electrolyzers supply the gas turbine with hydrogen in a location where the average wind speed is 5.12 m/s, while 600 m^2 solar panels can operate the auxiliary boiler during the day.

Finally, the capital cost of the renewable system is higher than the capital cost of the power plant which is restricting for the general usage of those systems. It is very important for the future viability of these systems to increase the efficiency and to reduce at the same time the cost of hydrogen production by water electrolysis.

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