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Τμήμα Ηλεκτρολόγων Μηχανικών και Μηχανικών Υπολογιστών

Αποθήκευση Υδροηλεκτρικής ενέργειας μέσω αντίστροφης αντλίας

Διπλωματική εργασία
από

Κατσιβελάκης Μιχαήλ, Τσαντζάλης Σοφοκλής

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Declaration of Authorship

We, Katsivelakis Michail, Tsantzalis Sofoklis, declare that this thesis titled, ”Reverse Hydro Pump - Storage” and the work presented in it are my own. I confirm that:

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- I have acknowledged all main sources of help.
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Katsivelakis Michail, Tsantzalis Sofoklis
Volos, October, 2018

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Reverse Hydro Pump - Storage

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Abstract

The global effort to decarbonise electricity systems in combination with the global warming and other environmental concerns has led to gradient development of variable renewable energy generation technologies. Hydropower is a form of RES (Renewable Energy Sources) that is quite mature, with many years of development, and popular. Due to that, the generating methods and the turbine technology to produce electricity are going to be presented along with the largest power plants in the world.

In this thesis we will examine a form of hydropower, the pumped-storage technology. The pumped hydro energy storage (PHES) is a well-established and commercially-acceptable technology for utility scale electricity storage that was first appeared in the 1890s. Pump storage makes use of two reservoir, an upper and a lower. During off-peak hours, when the energy demand is low, the lower reservoir pumps water to the upper and during the hours when energy is needed, the upper reservoir sends the water to the lower, producing on that way electricity. Operational, technological characteristics and design features are presented for planning purposes.

Moreover, Raccoon Mountain, a facility that became the model of PHES power plants worldwide, is going to be presented. In addition, reference is made about the prospects and the future projects of PHES plants worldwide. Possible locations of future Pumped-Storage schemes in Greece will be examined depended on the height, the purpose and the reservoir capacity of the dam.

A case study is going to be done about the application of Pumped-Storage technology on a conventional existing hydropower plant in Pournari, Greece. Calculations of how efficient is pumped-storage technology are going to be examined for the combination of Pournari I and Pournari II as a Pumped-Storage project. The operation of the combined project of the two dams is simulated and the energy results are analyzed. Finally initial, operational and maintenace costs of a PHES project are discussed. A brief economical evaluation of our case study for Pournari I and Pournari II is done.

Reverse Hydro Pump - Storage

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Greek Abstract

Η παγκόσμια προσπάθεια για να απαλλαγεί η παραγωγή ηλεκτρισμού από υδρογονάνθρακες σε συνδυασμό με την παγκόσμια αύξηση της θερμοκρασίας και άλλα περιβαλλοντικά προβλήματα έχει οδηγήσει στη ραγδαία ανάπτυξη των ανανεώσιμων πηγών ενέργειας (Α-ΠΕ). Η υδροηλεκτρική ενέργεια ειναι μια ΑΠΕ αρκετά ώριμη, με πολλά χρόνια ανάπτυξης και αρκετά δημοφιλής. Εξαιτίας αυτών, σε αυτή τη μελέτη θα αναφέρουμε τις μεθόδους παραγωγής, τις τουρμπίνες και τα μεγαλύτερα εργοστάσια σε παγκόσμιο επίπεδο.

Σε αυτή τη διατριβή θα εξετάσουμε μια μορφή υδροηλεκτρικής ενέργειας, την τεχνολογία της αντλησιοταμίευσης. Η τεχνολογία της αντλησιοταμίευσης είναι μια καλά εδραιωμένη και εμπορικά αποδεκτή τεχνολογία για την αποθήκευση ηλεκτρικής ενέργειας η οποία εμφανίστηκε για πρώτη φορά στη δεκαετία του 1890. Η τεχνολογία της αντλησιοταμίευσης χρησιμοποιεί δύο δεξαμενές, μία άνω και μία κάτω δεξαμενή. Κατά τις ώρες όπου οι ενεργειακές απαιτήσεις είναι χαμηλές, η κατώτερη δεξαμενή αντλεί νερό στην πάνω δεξαμενή, ενώ κατά τη διάρκεια των ημερών όπου οι ενεργειακές απαιτήσεις είναι μεγάλες, στέλνει το νερό στην κάτω δεξαμενή παράγοντας ηλεκτρισμό μέσω τουρμπίνας/στροβίλου με αυτόν τον τρόπο. Τα λειτουργικά, τεχνολογικά χαρακτηριστικά καθώς και τα χαρακτηριστικά του σχεδιασμού παρουσιάζονται και αναλύονται για σχεδιαστικούς σκοπούς.

Ακόμη, θα παρουσιαστεί το εργοστάσιο στο Ρασσοον Μουνταιν το οποίο αποτέλεσε πρότυπο για εργοστάσια αντλιοταμίευσης παγκοσμίως. Επιπλέον, γίνεται αναφορά για τις προοπτικές και τα σχέδια της αντλιοταμίευσης σε παγκόσμιο επίπεδο. Θα εξεταστούν πιθανές τοποθεσίες για χρήση αυτης της τεχνολογίας στον ελλαδικό χώρο με βάση το ύψος, το σκοπό και τη χωρητικότητα της δεξαμενής.

Τελικά θα γίνει μία μελέτη, για την εφαρμογή της αντλιοταμίευσης στο υπάρχον υδροηλεκτρικό εργοστάσιο στο Πουρνάρι. Θα γίνουν υπολογισμοί με σκοπό να εξεταστεί η απόδοση της τεχνολογίας αυτής σε ένα πλάνο με δεξαμενές το Πουρναρι Ι(άνω) και το Πουρνάρι ΙΙ(κάτω). Διεξάγεται προσομοίωση της λειτουργίας του συνδυασμένου έργου των δύο φραγμάτων όπου υπάρχουν υδροηλεκτρικά εργοστάσια και αναλύονται τα ενεργειακά αποτελέσματα της άνωθεν έρευνας. Συζητούνται τα αρχικά, επιχειρησιακά κόστη και τα κόστη συντηρησης ενός έργου αντλιοταμίευσης και γίνεται μια σύντομη οικονομική αξιολόγηση της μελέτης περίπτωσης για το Πουρνάρι Ι και το Πουρνάρι ΙΙ.

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Chapter 1

Introduction

1.1 The energy need

The energy need is essential for the human life. From a physical point of view energy is the ability of a system to produce work to another. The definition of work is the product of the force exerted on the distance.
Every human activity demands huge amounts of energy and its absence can lead to various problems. Energy is very important for mankind and changes in energy supply and price can alternate the living standards, make economies bloom or fall. The modern way of life, regardless of country, is constantly increasing the energy demands, because basic human needs like transportation, industry, cooling, heating and lightning couldnt be achieved without energy. Moreover, the energy requirements and usage determines the development level of a country. This can be strengthened from the fact that the industrial revolutions of the past were leaned on the energy production. Finally high energy demands cause energy problems due to depletion of fossil fuels. [19]

1.2 The energy problem

Despite all that reliance the modern society has on energy, the situation nowadays is not ideal. Human beings through the passage of time used wood and for the last two centuries fossil fuels (fissile material, natural gas, oil, carbon). The development of living standards based on the great usage of cheap energy sources, mainly on fossil fuels. The dependence on them and the non-democratic allocation led at the core of the energy problem, which is the depletion of the fossil fuels. Only a few countries have almost all fossil fuel reserves. Almost the 85% of the human activities come from the combustion of fossil fuel. The energy problem was first formulated in the early 1950s. The industrial growth was based on fossil fuels and their excessive usage lead to an energy crisis in the decade of 1970 and the summer of 2008 where the price of barrel oil skyrocketed and reached 140 USD. The increase of earth population combined with the continuous increased energy needs will lead to an even larger consumption of energy in the near future. Another part of the energy problem is the inability to predict when the reserves will dry out and the instability they offer. Finally a significant factor of the energy problem is the pollution of the environment. The mining of fossil fuels and their usage can cause irreversible problems like greenhouse effect, pollution of the water resources. [19] [26]

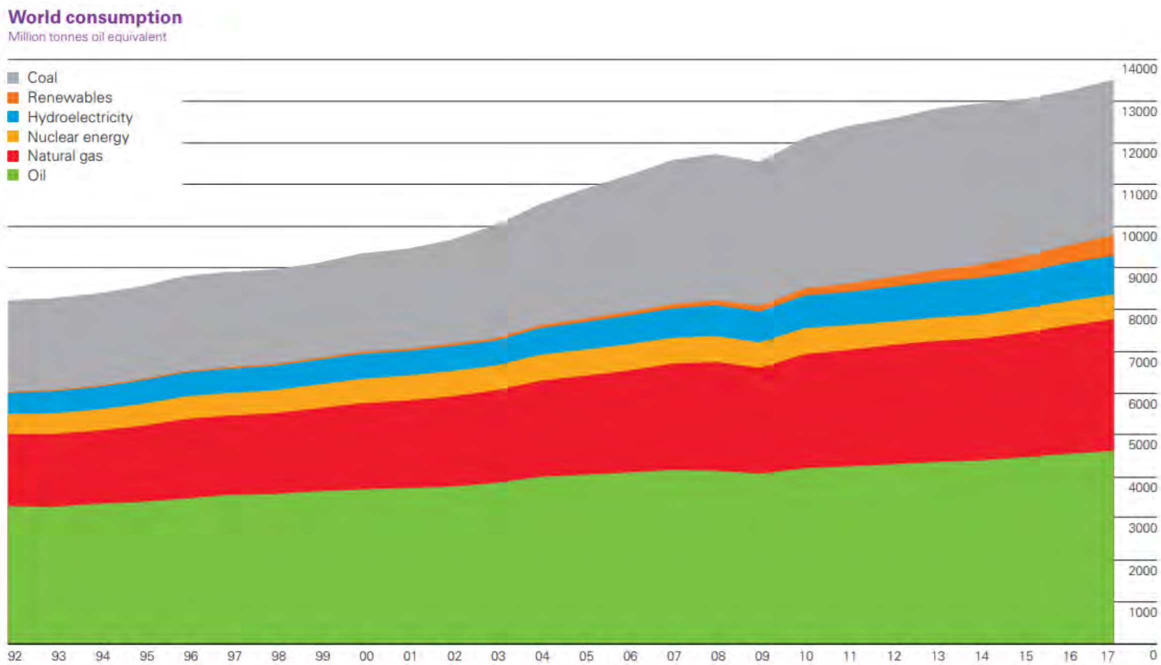

Figure 1.1: World primary energy consumption grew by 2.2% in 2017, up from 1.2% in 2016 and the highest since 2013. Growth was below average in Asia Pacific, the Middle East and S. & Cent. America but above average in other regions. All fuels except coal and hydroelectricity grew at above-average rates. Natural gas provided the largest increment to energy consumption at 83 million tonnes of oil equivalent (Mtoe), followed by renewable power (69 Mtoe) and oil (65 Mtoe). (BP Statistical Review of World Energy 2018)

1.3 The Environmental Consequences

The excessive use of fossil fuels created many problems in the environment and the animal life. The energy production from fossil fuels is inextricably linked to air and water pollution. Consequences to the environment come from the mining, the production and the transportation of fossil fuels and their combustion in order to produce energy. Usually the area of mining are mines for the export of crude oil, oil and natural gas. As far as concerned the mining, the greatest impact on the environment lies in the blocking of large rural areas. The usage of land has social and environmental impacts. Often, residents are hostile and opposed to any land use for energy or other activities (landfill of waste, industrial activities). These kind of behavior is known as the not-in-my-backyard syndrome, NIMBS. Abuse of land combined with the effect of the acid rain, where sulfur and nitrogen are produced from the combustion of oil, result in degradation of the areas. Often the transportation of fossil fuels through pipelines and tankers have leaks so there is pollution on the natural environment. [19]

The main source of pollution comes from the production of energy. The first step for the energy production refers to the conversion of chemical energy into thermal. That can be achieved through combustion. The perfect combustion releases to the air CO_2 unlike to the imperfect combustion which requires oxygen from the atmospheric air and produces carbon monoxide (CO). Because of the atmospheric air sometimes nitro-oxides (NO_x) are produced and released in the atmosphere. Some fuels have sulfur in their substance and that is the cause that produce sulfur dioxide (SO_2) in the air. These gases are poisonous and extremely dangerous for the atmosphere and are a reason that in some areas the local people suffer from chronic bronchitis and in some extreme cases lung and larynx cancer. Moreover the increased emissions of combustion and other carbon gases, like methane (CH_4) or chlorofluorocarbons (CFC), are the main reason of the greenhouse effect because their radiation increases the temperature of the earth surface. Like in a greenhouse or in our car when it is exposed to the sun and temperature increases inside them so the earth is heated during the greenhouse effect. Earth keeps temperature between 0°C and 100°C due to the atmosphere. In nature, there is a balance where the energy that is produced in earth is released in the atmosphere and then in space.[19] [26]

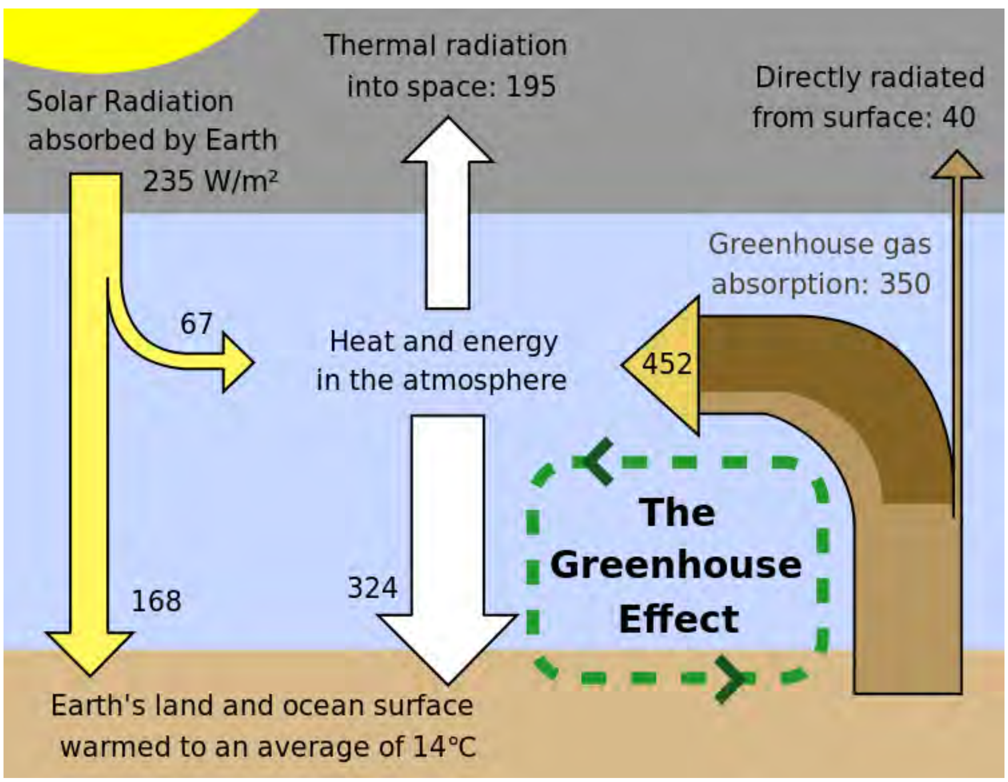

Figure 1.2: A representation of the exchanges of energy between the source (the Sun), Earth's surface, the Earth's atmosphere, and the ultimate sink outer space (Wikipedia).

This balance stabilizes the average earth temperature in 14 °C. These gases disturb this balance and the high concentration of CO_2 because the raise of the average earth temperature. It is estimated that by 2050 the temperature will increase by 1.5-6°C which is extremely critical to life and will affect the earth climate and the arctic areas the most because large icebergs will melt. This will cause many problems that can alter the world. The iceberg melt will cause the level of the seas to raise. It is estimated that by 2100 the raise will be around 0.1-0.5 meters. That means that there will be floods in many places that have low or negative height, like the areas around Mediterranean sea. Furthermore, there will be less rain due to the heat causing many areas to be drought and thus be deserted. The thermal energy from the oceans will create many typhoons and will change the direction of the water current in the seas resulting in the freeze of many Europe countries because there will be no heat current form the Mexico bay. Finally, many animals and plants will go extinct and the mankind will suffer from diseases that come from aquatic organism and diseases that are spread through bugs. [19] [26]

Another major environmental problem is the phenomenon of acid rain. Acid rain is caused by emissions of sulfur dioxide, oxides of nitrogen and ammonia. A more specific term is acid deposition consisting of two parts, liquid deposition and gas deposition. Liquid deposition refers to acid rain, mist and snow. The consequences which caused by acid rain are dependent from many factors like pH of acidic water, chemistry and its regulatory capacity of the soil and the surface water, species of marine organisms. Gas deposition is linked with acid gases and particulates which are transported by air on every surface. In the first stages of acid rain water is made more acid combined with gas deposition. The consequences of acid rain are enormous and destructive. pH reduction of waters, seas, rivers and lakes was found in 1950s due to the extinction of marine life in Scandinavian peninsula. In forests, the main impact which caused by acid rain is the smaller increase of trees, foliage reduction, injuries, and total destruction of the trees. Such damages are provoked when pH is under 5.1. In general it is estimated that 1 out 4 trees in Europe has been damaged by acid rain. For the mankind, acid rain consequences concern health problems which are transfered to men through the food chain or directly from rain. quatic organisms are sensible in pH under 5.5. Moreover, acid rain affects the food chain of some species because solubilizes and some nutrients are lost from the soil and can solubilize certain minerals that may be toxic to some micro-organisms, birds and animals. Finally there is corrosion of metallic materials, wear of certain structural elements materials and reduction of visibility especially at atmospheric concentration of sulfur dioxide 0.1 ppmv visibility is reduced to 8 km. [19] [26]

1.4 The Energy scene worldwide

Four main factors determine the global scene of energy system. The first factor is the rapid development and the falling cost of clean energy technologies. Next, is the the growing electrification of energy and the Chinas shift to an energy revolution. Last is the resilience of oil and gas stocks in the United States.

Nowadays there is a growing demand in global energy needs and they rise more slowly than in the past but still expand by 30% between today and 2040. This is the equivalent of adding another China and India to todays global demand. Moreover there is a stable growth of global economies at a rate of 3.4%, a population that expands from 7.4 billion today to more than 9 billion in 2040 because there is a trend towards urbanization. A little less than 30% of the global energy demand comes from India whose share of global energy use rises to 11%

by 2040. Southeast Asia has rapid development in energy demands with demand growing at twice the pace of China.

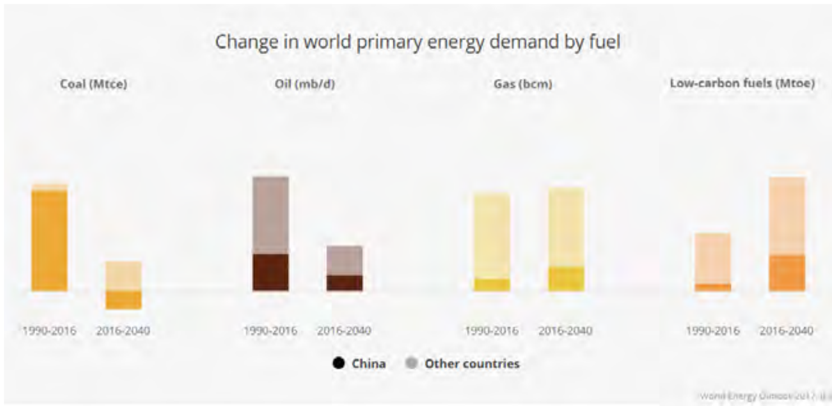

Figure 1.3: Change in world primary energy demand by fuel (IEA World Energy Outlook 2017).

The high energy demands lead to the rapid advance of the Renewable Energy Sources. Renewable sources of energy meet 40% of the increase in primary demand and their explosive growth in the power sector marks the end of the boom years for coal. Renewables capture two-thirds of global investment in power plants to 2040 as they become, for many countries, the least-cost source of new generation. In the European Union, RES account for 80% of new capacity and wind power leads in electricity after 2030. Finally, growth in RES is not limited to the energy sector, because RES can be used directly for heating or mobility reasons. Another factor, as mentioned, that shift the global energy scene is the electrification of the energy. The electricity is the source that powers the modern technology and the households. Thus, there is a great increase in the electricity production and consumption. The electricity makes up 40% of the rise in final consumption to 2040. China is the first consumer of electricity having a rapid pace in its demands. This can be seen from the image below along with the demands of other regions. Future needs in electricity and the challenge of decarbonizing power supply, explain the upward trend in oil and gas investments in electricity. New vulnerabilities need to be addressed due to the increasing use of digital technologies across the economy.

Another great factor that changes entirely the energy scene is the entrance of China in the energy market. China aims at a different policy in energy and the transition towards a more services-based economic model is moving the energy sector in a new direction. Moreover, through this policy China seeks to reduce the level of pollution. China will play a very important role determining global trend around clean energy. This countrys clean energy development combined with technology exports and outward investment could be the key factor behind the low-carbon transition. One-third of the worlds new wind power and solar PV is installed in China in the New Policies Scenario, and China also accounts for more than 40% of global investment in electric vehicles (EVs).

Concerning global gas demand, China is ranked second as its projected imports of 280 billion cubic meters (bcm) in 2040. In addition China overtakes the United States as the largest oil consumer around 2030, and its net imports reach 13 million barrels per day (mb/d) in 2040. China is a major market of coal, however coal use peaked in 2013 and projections

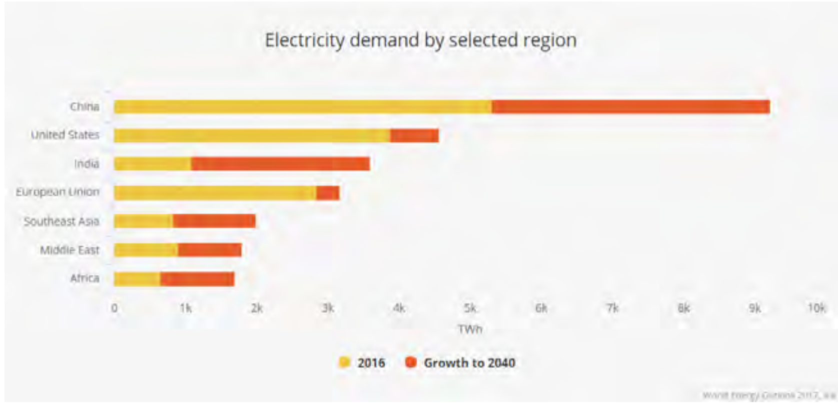

Figure 1.4: Electricity demand by selected region (IEA World Energy Outlook 2017).

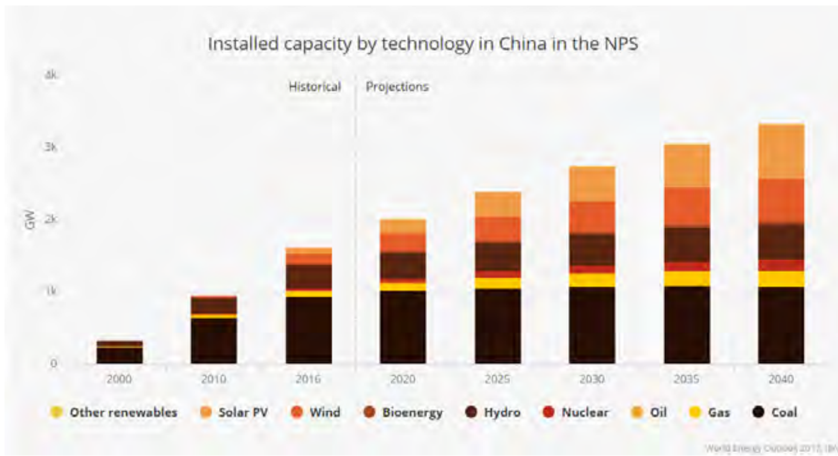

Figure 1.5: Installed capacity by technology in China in the NPS (IEA World Energy Outlook 2017).

suggest that coal use is set to decline by almost 15% over the period to 2040.

Finally, United States gas and oil stocks are a factor that will play a major role in the energy scene in the near future. US can exploit new resources with efficient cost and thus in the near future will be the main exporter of oil with 50% higher than any other country. According to WEO (World Energy Outlook 2017 by International Energy Association) projections, the 8 mb/d rise in the US oil output from 2010 to 2025 will be the highest in the history of the oil market. These events will have a great impact and will reorder the international trade flows of the oil and gas industry. [6]

1.5 Turn to RES (Renewable Energy Sources)

Energy and environmental issues are particularly important for mankind as they directly affect our lives. Human beings for the last two centuries used fossil fuels (fissile material, natural gas, oil, carbon), so their excessive usage results in the exhaustion of conventional fuel supplies and energy reserves. As a result of this, the combination of growing demand of energy and the gradual deterioration of environmental problems has led modern societies to turn to energy saving techniques and particularly to the usage of Renewable Energy Sources (RES). A Renewable Energy Source (RES) is defined as a form of energy that is not exhausted in the distance future of humanity and can be used in a stable and reliable way. According to International Energy Association (IEA) RES are classified into:

1. Solar Power
2. Hydropower or Hydroelectric Energy
3. Wind Energy
4. Combustible Renewables and Waste (CRW), Biomass
5. Geothermal Energy
6. Tidal Energy
7. Wave Energy
8. Oceanic Thermal Energy

The main advantage of the RES is that they permit infinite exploitation, that means that they can be used as energy sources without being depleted. Moreover, they help mankind to stop the excessive usage of fossil fuels that cause enormous problems. One of the greatest benefits is that RES are friendly to the environment and cause absolutely no harm to the human. As are a result of this RES limit the energy problems that affect the environment, for that reason RES are also called benign. They also require low cost on energy production and the cost is in majority the power plant that needs to be built. In addition, another economical advantage is that their price is independent from the cost of the fossil fuels that is greatly variable by the economical circumstances. Finally, due to the technological development, RES can only be co-used with the fuels and because of that they often called additive. [19] [26]

The main and absolute renewable energy source is the sun with capacity energy more than 160 times the stored energy on earth. Sun rays which fall on earth on an annual basis is 15000 times greater than the annual primary energy consumption. All Renewable Energy Sources with the exception of Geothermal and Tidal power are considered to be indirect effect of the sun because cycle of water, wind power and plant growth are result of the solar radiation which falls on Earth. The direct form of the energy that comes from the sun is the solar energy. This type of energy is infinite and due to this has high potential. Another great advantage it offers is that it cause absolutely no harm to the environment unlike other RES which cause minor problems. The only drawback solar energy has is that it cant be used during nights and days that there is no sun and the weather is cloudy or rainy. [19]

Geothermal is a renewable and inexhaustible energy source with high performance, which can cover heating and cooling demands and in some cases, it can produce electrical energy. Geothermal is an eco-friendly form of energy and has low costs (not so expensive fixed cost). It is produced by the stored heat in the subsoil due to the high temperatures of the earth core. The temperature of the geothermal fluid or steam varies from 25°C to 360°C. Nowadays the total installed power of Geothermal Plants worldwide is 9000MW and the main thermal use of geothermal energy worldwide is related to greenhouse and aquaculture facilities heating. [20]

Biomass is every material (solid, liquid and gas) that consists of carbon and can be converted into energy (bioenergy). These materials can be directly burnt for heat and power production or can be transformed into biofuels. In general, biomass is the material which has organic origin and in fact, any material that comes directly from the plant world, or indirectly from the urban, industrial and rural waste, is included in it. Specifically, biomass consists of wood, wood waste, plant and forest residues, animal waste, products from the processing of fruits and the plants from energy crops. [19]

The two main sources of bioenergy are the energy crops and the waste. Biomass is very eco-friendly and that is the main reason it draws the attention of many researchers. That is because it is the result of the photosynthetic activity of the land and aquatic plants and demands secondary solar energy. These plants transform the CO_2 from the atmosphere and the solar power into glucose. [19]

In addition, Biomass can be exploited for the production of liquid biofuels. The most important biofuel is Biodiesel, which is produced by vegetable oils, animal fats, various energy crops, algae, but also a variety of recycled oils. The main use of Biodiesel is as a diesel fuel, because its chemical composition is similar to that of diesel. Another important biofuel is Bioethanol, which is derived mainly from the fermentation of plants like sugar beet, corn, barley and wheat. Just like Biodiesel, Bioethanol is pre-blended in quantities of diesel. A drawback Biomass offers is the difficulty in transportation. [19]

Wind power is the energy that is produced from the kinetic energy of the wind that is turned into electricity. It is an energy source with a relatively low cost and can produce huge amounts of power without the combustion of fossil fuels and the environmental problems that they cause. Wind power is a form of energy that is used by human for centuries and at the end of the 19th century operated about 100000 wind power grids in Europe. Wind is a source of energy that comes from the differences in atmospheric pressure which come from the uneven heating on surface of the earth and the surface of the sea. As a result of this we conclude that wind power is an indirect source of solar energy. Nowadays we can easily convert wind energy to kinetic energy and then to electric energy with the help of wind turbines. Wind turbines demand large scale facilities and the preferred ground for installation of a wind park is near the sea. The overall capacity of all wind turbines installed worldwide by the end of 2017 reached 539.291 Megawatt and wind power is a solution to the problem of the electricity production. All wind turbines installed by end of 2017 can cover more than 5% of the global electricity demand and n increasing number of countries have reached a double-digit wind power share, including Germany, Ireland, Portugal, Spain, Sweden or Uruguay. Finally, wind power is an efficient renewable source of energy with a lot of prospects for the future in the production of electricity. [13] [19]

Tidal energy is a form of hydropower that converts the energy of the tides into electricity or other useful forms of power. The tide is created by the gravitational effect of the sun and the moon on the earth causing cyclical movement of the seas. The loss energy as heat due to friction caused by the tides appeared to have helped the time of rotation of the earth to increase from about 8 hours to 24 hours. As a result of this the ultimate source of energy for the tides may be the rotation of the earth. The main advantage of tidal energy is the great stability and predictability it offers, because it is well known when tides will appear. [19]

Wave Energy is the energy that comes from the wind waves due to the solar radiation. It is a form of energy that is not widely used and has an impact on the environment because of the damage to the marine life and the noise it causes. [19]

Oceanic Thermal energy is a form of energy that is produced from the temperature difference between surface hot water and the cold water in the bottom of the sea. This type of energy has huge potential and is predictable. A drawback of the energy of the oceans is that the appropriate power plants are quite expensive. [19]

Hydroelectric power is a renewable form of energy that comes from falling from rivers or lakes with the help of Hydro turbines. Specifically, water falls due to gravity, which causes kinetic energy to be converted into mechanical energy, which in turn can be converted into a usable form of electrical energy. Wave, Oceanic thermal and tidal energy is part of hydropower. Hydroelectric energy is a highly predictable form of energy and is also efficient. Hydropower will be analyzed in the next chapters. [19]

Chapter 2

Hydroelectric Power

2.1 Definition of Hydropower

Water makes up about 73% of the Earths surface. This fact encourages mankind to use water in order to produce usable energy for their needs. The most common energy by using water as the source is the hydropower or hydroelectric power. Hydroelectric power is the most commonly used renewable energy resource. It can be stored in the form of impounded water and is relatively nonpolluting and it is an indirect effect of solar energy. Almost 1/4 of the underlying radiation of the sun is used in the evaporation of water. Water vapor in the atmosphere are considered to be an enormous energy storage but most of this energy is not able to be harnessed, because is condensed in the form of clouds and is evaporated again. Just 0.1% of the total recirculated water vapor-water energy is the available hydro potential. This type of energy is produced from the falling water by the effect of the gravity with the help of turbines. The kinetic energy of the fall is then converted in mechanical and then into a usable form of electrical energy. Water (like any other material) at a height represents stored dynamic energy which is given by the formula:

$$PE = m \times g \times h \tag{2.1}$$

where m is the mass of water (kg), g is the acceleration of gravity (9,81 m/s^2) and h is the net waterfall height (m). The power of the waterfall is given by the formula:

$$P = g \times M \times h \times n \tag{2.2}$$

, where M is the mass flow (kg/s), h is the difference of height between the turbine and the surface of water (m), n is a performance factor due to the energy loss which range is between 0.8 and 0.95, g is acceleration of gravity. The formula can be written:

$$P(kW) = 10 \times n \times Q(m^3/s) \times h(m) \tag{2.3}$$

where Q is the volumetric flow rate (m/s^3). With the help of the formula:

$$P = g \times M \times h \times n \tag{2.4}$$

, can be appreciated the maximum price of the world hydroelectric potential. On planet it is estimated that the annual rainfall land is 10^{17} kg and the average altitude of the land from the sea level is slightly larger from 800 m. As a result of this the annual add in the yearly addition to the energy ”warehouse” of water is 8 * 10^{20} J (200000 TWh). This price is more than twice that of the world consumption of primary energy. Unfortunately there can be no technology to utilizes every drop of rain so the world-wide potential of hydro power is much smaller. The final estimation about the hydroelectric potential is about 2-3 TW of power, with annual production 12000-20000 TWh. [25] [19]

Hydropower energy provides many important advantages. Hydropower uses the water as fuel but it doesnt consume water while generating energy. Moreover hydropower plants and installations produce a number of economic, social and environmental benefits. From the economic perspective, it helps industry by creating job opportunities, forming forward and backward linkages of the construction input (material) and it is a low cost energy compared to other energy sources. Regarding social effects, hydropower is capable of preventing floods, supplying drinking water, water for irrigation and industrial needs as well as a variety of opportunities notably fishing, swimming and boating, without harming on the ecosystem and air quality. At the same time hydropower energy contributes in the development and regional cooperation, allocate scarce water resources and to reduce financial, social and environmental risks. In addition, the penetration of variable renewable energy sources such as backing up the wind and solar energy systems which are vulnerable to weather conditions, help the traditional roles of hydropower evolution. [22]

2.2 Historical Overview

Hydropower is not something new that is used the last decades but dates 5000 years. Archaeologists report that the idea of using dams for water storage is conceited around 3000 BC. The first written scripts regarding hydropower suggest that ancient Greeks used water wheels in order to make flour from wheat and around 200 BC the Chinese used the water power in order to create paper. Vitruvius around 100 BC described the first water mill and during Roman years, the whole territory had water mills installed with the largest being able to produce 15KW. There are reports that water wheels were found at later dates in Scandinavia.

From 1500-1800 there were many improvements to the water mills, the most important sending the water from the upper side of the mill, which enabled greater performances. The availability of water power has been linked with kick-starting economic growth. When Richard Arkwright set up Cromford Mill in Englands Derwent valley in 1771 to spin cotton and so set up one of the worlds first factory systems, hydropower was the energy source he used. Indeed he was very excited of the benefits of hydro, so he started using a steam engine six years later in order to pump water into the mill pond rather than to drive machinery directly. Hydropower set the industrial revolution of the country running. In many places of the world hydropower has played an equally major role in increasing and transforming development. Until the 19th century hydropower was mainly used for agricultural reasons, for cutting woods and weight lifting. But then in the US and UK started its exploitation in order to produce electricity. In the Cragside country house in Northumberland, England, in 1878 the first hydroelectric project was born in order to power a single lamp. In 1879 the first hydroelectric power plant was built in Niagara Falls and the electricity enabled the usage of lamps in the city. In 1881 Surrey (UK) hydroelectric plant opened and in 1882 Wisconsin

(US), the first plant to serve a system of private and commercial customers opened. Generally in North America, hydropower plants were installed at Grand Rapids, Michigan (1880), Ottawa, Ontario (1881), Dolgeville, New York (1881), and Niagara Falls, New York (1881). They were used to supply mills and light some local buildings. By the turn of the 20th century the technology was spreading round the globe, with Germany producing the first three-phase hydro-electric system in 1891, and Australia launching the first publicly owned plant in the Southern Hemisphere in 1895. In 1891 electricity from hydro power plants was being used all around US and could also be transmitted for 150km. At Niagara falls the Edward Dean Adams Power Plant, the worlds largest hydroelectric development of the time is constructed. A hydroelectric station was constructed on the Xindian creek near Taipei in 1905, with an installed capacity of 500 kW. Then in mainland China the first power plant was built in 1902 the Shilongba plan in the Yunnan province and was put into operation in 1912. Upon completion Shilongba had an installed capacity of 480 kW today it is still in operation with an installed capacity of 6 MW. During the next years there can be seen a rapid development and hydroelectricity is being produced by the majority of countries. In the first half of the 20th century, the USA and Canada led the way in hydropower engineering. At 1345 MW, the Hoover Dam on the Colorado River became the worlds largest hydro-electric plant in 1936, surpassed by the Grand Coulee Dam (1974 MW at the time, 6809 MW today) in Washington in 1942. Large hydropower developments took place in Canada, the USSR, and Latin America, from the 1960s through to the 1980s. Brazil and China has become world leaders in hydropower over the last few decades. The Itaipu Dam, straddling Brazil and Paraguay, opened in 1984 at 12600 MW (it has since been enlarged and uprated to 14000 MW) and today is only surprised in size by the 22500 MW China Three Gorges Dam, which opened in 2008.

Into the 21st century, hydropower continues to catalyse growth around the world. Hydropower has played a key role in transforming Brazil into the seventh largest country by GDP in 2012. The investment in hydropower by Brazil helped the increase in electricity. In 2010, Brazil produced 349000 GWh of electricity, and by 2011 this had increased by 40 per cent to 489000 GWh. Remarkably, just 2 per cent of this energy came from imports, and around 80 per cent from hydropower. Finally, Brazil is just one example of the massive stimulus to economic growth that hydropower can provide; as we look towards the future the technology has a huge role to play in bringing growth and prosperity to the developing world. [1] [19]

2.3 Turbines and Generating methods

Hydropower is the power generated by harnessing energy from the moving currents. Mankind has used hydropower for many centuries and has developed as the time passed greater technologies that helped produced even greater amounts of electricity. Nowadays, this technology have advanced in a level that can be considered, according IEA, a mature technology. The current technology produce electricity through the transformation of the hydraulic energy into mechanical energy, which activates the turbines of the facility that are connected to a generator. Then the electricity is transmitted through lines or partially used in order to generate the facility. The hydroelectricity that is produced is the biggest contributor to the renewable electricity worldwide, according to IEA. The hydropower is a multilateral energy and can have different results to different power systems or methods. This versatile nature of the energy can have, moreover, different adaption to the environment constraints. That means that the stations that are extremely site-specific and for their installations the local topography and hydrology were researched. [19]

2.3.1 Turbines

The turbines were created in 1832 from the French engineer Benoit Fourneyron and had about 80% better performance than the water wheels of that age. Turbines are major parts of an hydroelectric power plant and every generating method requires turbines in order to produce electricity. A turbine converts the energy from falling water into rotating shaft power. The site characteristics, the head and flow or volume available are the dominant and determine the best selection among the turbines for any particular hydro. Selection also depends on the desired running speed of the generator or other device loading the turbine. Moreover, other deciding factors are the depth of the turbine, the efficiency and the cost. Hydro-turbines convert water pressure into mechanical shaft power, which can be used to drive an electricity generator, or other machinery. The power available is proportional to the product of pressure head and volume flow rate. The general formula for any hydro systems power output is:

$$P = h \times r \times g \times Q \times H \tag{2.5}$$

where P is the mechanical power produced at the turbine shaft (Watts), h is the hydraulic efficiency of the turbine, r is the density of water (kg/m^3), g is the acceleration due to gravity (m/s^2), Q is the volume flow rate passing through the turbine (m^3/s), and H is the effective pressure head of water across the turbine (m).[36] Hydraulic efficiencies range 80 over to 90% for the best turbines, although this will reduce with size. Turbines can be crudely classified as high-head, medium-head, or low-head machines. But this is relative to the size of machine: what is low head for a large turbine can be high head for a small turbine: for example a Pelton Turbine might be used at 50 m head with a 10 kW system but would need a minimum head of 150 m to be considered for a 1 MW system. Electricity generation requires a shaft speed as close as possible to 1500 rpm to minimize the speed change between the turbine and the generator and this is the main reason for the usage of different types of turbines are used at different heads. Moreover the speed of any given type of turbine tends to decline in proportion to the square-root of the head, so turbines which are faster under certain conditions need to be installed to low-head sites. Principle of operation is the main division factor of turbines, so we have 2 main types of turbines: the Impulse Turbines and the Reaction Turbines. Every turbine took its name from its creator. The selection of any type of hydropower turbine for a project is based on the head and the flow or volume of water at the site. Other deciding factors are efficiency, cost and how deep the turbine must be set. [36]

Impulse Turbines

The main principle of operation of Impulse Turbines is that the impulse turbine uses the kinetic energy of water to drive the runner and discharges to atmospheric pressure. Jets of water are responsible for the movement of impulse turbine and the runner operates in air, the water remains at atmospheric pressure before and after making contact with the runner blades. Water that falls into the tail water after striking the buckets has little energy remaining, thus the turbine has light casing that serves the purpose of preventing the surroundings against water splashing. Systems with high head and low flow are usually use impulse turbines. There are 3 main types of impulse turbine in use: the Pelton, the Turgo, and the Crossflow (the latter is also known as the Banki turbine). [35]

Pelton: This form of turbine has a wheel containing a series of split buckets (vanes) set around its rim. Each bucket individually is hit by a jet of high pressure water which is directed tangentially at the wheel. The jet is split in half and each half is turned and deflected back almost through 180. Nozzles issue the jets of water, each nozzle with an axis in the plane of the runner and a needle (or spear) valve to control the flow. In order to stop the turbine, if the turbine approaches the runaway speed due to load rejection, the jet is deflected by a plate so that it does not impinge on the buckets. As a result of this the needle valve is closed very slowly, so maintains the overpressure surge in the pipeline to an acceptable minimum. Buckets are designed to keep exit velocities to a minimum because the kinetic energy of water leaving the runner is lost. Draft tubes are not necessary due to the fact that e the runner are positioned above the maximum tail water to permit operation at atmospheric pressure. Pelton turbines are usually applied in systems with large water heads. Finally unlike the Francis turbine, Pelton and cross flow turbines can operate at high efficiencies even when running below their design flow. [35]

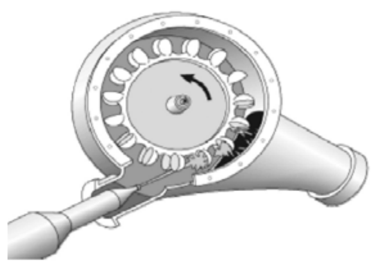

Figure 2.1: Pelton Turbine (”Review of small hydropower technology”, David Kilama Okot)

Cross-Flow (Banki Turbines): The cross flow (or Banki) turbine has a drum-like rotor and uses an elongated, rectangular-section nozzle which is directed against curved vanes on a cylindrically shaped runner. The efficiency of Cross-Flow turbines is less than the modern day turbines (i.e. Pelton, Turgo, Francis and Kaplan), although it can accommodate larger water flows and lower heads. A jet of water enters the turbine, thus gets directed through the guide-vanes at a transition piece upstream on the runner which is built from two or more parallel disks connected near their rims by a series of curved blades. The guide vane directs the flow to a limited portion of the runner with final destination the entrance of the turbine. The design of the turbine allows s water to flow twice through the blades. In the first stage water flows from the outside of the blades to the inside, in the second stage the water passes from the inside back out. Significant shock losses are caused as the flow leaves the first stage attempts to cross the open center of the turbine and then as the flow enters the second stage, a compromise direction is achieved.[35]

Turgo: This type of turbine is similar to the Pelton, but with different shape of the buckets and the jet strikes the plane of the runner at an angle (typically 20o). The entrance of the jet of water in the runner takes place through one side and the exit through the other side. The flow rate through a Turgo turbine is not limited by the discharged fluid interfering with the incoming jet, in contrast with the pelton turbine. As a result of this, a Turgo turbine can have a smaller diameter runner compared to that of a Pelton turbine with an equivalent power output. A high running speed of Turgo turbine than Pelton turbine, can make a direct coupling of turbine and generator more likely, as a result of this the overall efficiency is increased and the maintenance is decreased. Systems with large water heads favor the operation of Turgo turbines. [35]

Reaction Turbines

The Reaction turbines generate electricity from the mutual action of pressure and by moving water. When the rotor is fully immersed the water and its completely enclosed in a pressure casing the pressure causes the blades to start rotating. The turbines of this type are suitable for sites with lower head and greater flow. There are four kinds of reaction turbines, the Propeller, the Francis, the Kinetic/Free flow and the Archimedes screw.[35]

Propeller: These turbines are more suitable for sites with lower head and have an axial flow runner whose blades number can vary from three to six. In this type of turbines, if the water has a swirl before entering the runner, the efficiency is higher. The methods that are used for the initial rotation of the water include some guide vanes mounted in the upstream of the runner and a snail-shell that forces the water to enter with the swirl. The propeller type turbines are efficient for sites with low water heads. There are several propeller type turbines, the bulb turbine, the Straflo, the tube turbine but the most important and most used is the Kaplan. This turbine has a great advantage of having higher efficiency than other propeller under different conditions. Kaplan turbines use guide vanes and have adjustments in the blades of the runner for the inlet swirl. These turbines have commonly a higher cost and can only be economical in larger scale power plants. [35]

Francis: Francis turbines are the most common reaction turbines. They have a radial or mix-radial axial flow runner which is connected commonly to a spiral case with internal guide vanes. The axial to the runner entrance of flowing water causes the turbine to start spinning, thus producing energy and then releasing the water outwards. The runners with large diameter have as main material stainless steel and the runners with small diameter are fabricated with aluminum bronze. Francis turbines doesnt have only the runner but they have two more important components the draft tube and the wicket gates. These kind of turbines are the best choice for a medium water head power plan because their efficiency can be greater than 90%. When the water availability is less than the designated, these turbines are less efficient. Francis turbines can also be used in open flume in smaller head power plants and can also be attached in a penstock and steel spiral cases in higher head power plants. [35]

Kinetic/Free flow: These type of turbines make use of the kinetic energy of the flowing water instead of the potential energy that comes for the head. Kinetic turbines are great for

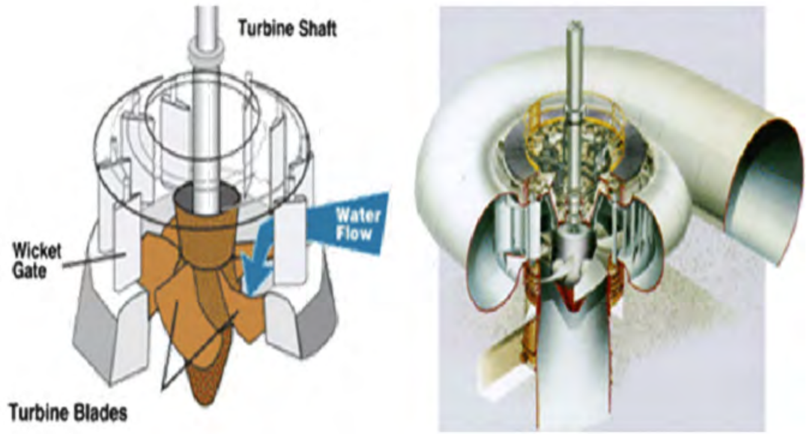

Figure 2.2: Typical propeller turbine. ("Review of small hydropower technology", David Kilama Okot)

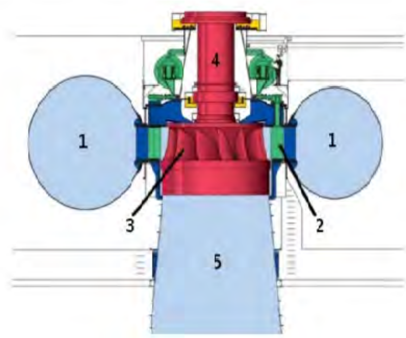

Figure 2.3: Francis turbine: 1) Spiral casing, 2) Guide vanes, 3) Runner, 4) shaft, 5) draft tube. Hydroelectric Power in Present and Future Energy Systems, Tjalve Magnusson Svendsen.

low head sites such as rivers, man-made channels and ocean currents. They make use of the natural pathway of the water so the don't require any diversion through channels or pipes, although these turbines can be used in these systems. [35]

Archimedes Screw: There is not a standard size for the turbine but the size is connected with the site that the screw is about to be installed. The head of the water determines the length of the screw (the higher the head, the longer the screw) and the flow the diameter (the more water flow, the bigger the diameter).The most common material of the screw is the steel. The operation of the screw starts with the entrance of the water and the rotation of the screw. This causes the gear box and the generator to turn on and thus electricity is produced. This screw is great for low water head sites and great water flow. In this case, the length can be from 2-10m. The advantages of Archimedes screw over the conventional turbines are that they have lower operational and maintenance cost than cross-flow or propellers, there is no danger from fish, debris or flowing objects, because they pass through the screw and the water and turbine operation, unlike other turbines, can be seen. [35]

2.3.2 Generating Methods

Nowadays, there are four ways to produce hydroelectricity, the Storage Hydropower, the Pumped-Storage Hydropower, the Run-of-River Hydropower and the Offshore Marine and other technologies. The first three are quite advanced and mature, but the latter is still growing and has great potential in the future.

Storage Hydropower (Dam) Storage Hydropower is what we call a Dam. The facility of this technology uses the dam in order to enclose the river or the lake water and thus store it for the release when it is necessary. When the dam opens and the water is released from the reservoir the turbines start working and the generators that are connected to them are starting to produce electricity. The storage technology is operated to provide base-load power, as well as peak load through its ability to be shut down and started up at short notice according to the demands of the system. It has the ability to operate independently from the inflow for many weeks and months. The dams have also the benefit to protect from floods which is very important. But the primary advantage of hydro facilities with storage capability is their ability to respond to peak load requirements.

Run-of-River Hydropower Facilities of this type channel the flowing water from rivers through a canal or penstock to drive a turbine. These power plants have short water storage and they have the great advantage of suppling electricity continuously. That means that their installation is to provide base load power to the electrical grid. These facilities, moreover, are flexible and can keep with the electricity demands.

Offshore Marine and other technologies This is a group of growing technologies that have great potential. Facilities of these type are producing electricity mainly from the seawater and more specifically from the currents of the waves. This is the electricity produced from relative types of hydropower, the tidal energy, the wave energy, osmotic and ocean thermal energy. The technologies that are used are similar to the hydroelectric.

Pump-Storage Hyropower This technology harnesses water which is cycled from a lower and an upper reservoir by pumps. When there is high electricity demand the water is released with the help of turbines back to the lower reservoir and thus electricity is generated. There are examples of pumped storage technologies that use the natural flow of the water. This technology can be combined with other renewable energies, like solar and wind. More for pumped-storage will be analyzed in the next chapter. [28]

2.4 Hydroelectric Power Plants

Nowadays hydropower is being used in many countries and is a great source to produce energy mainly because it is a result of the harnessing of the water. This is also enforced by the fact that hydroelectric power plants can last 2 to 10 times longer than the power plants that product energy from carbon and fuels. Moreover, if it is taken in account that hydroelectric energy it is environmental friendly, it is easily a great source of energy and a target for many countries.

Hydropower stations are categorized into three types based on their function: storage, run-of-the-river, and pumped-storage technologies. Rivers or creeks feed water to reservoirs in storage technologies. Run-of-the-river technologies harness the natural flow of streams. Water is channeled from a lake, river, or reservoir to a powerhouse in storage and run-of-the-river technologies. In addition hydroelectric power plants according to the size of their installed capacity are divided into small, medium and large.

Type	Capacity	Stream	Load
Small	Less than 10 MW	Run-of-the river	base
Medium	Between 10 and 100 MW	Run-of-the river	base
Medium	Between 100 and 300 MW	Reservoir	base and peak
Large	Greater than 300 MW	Reservoir	base and peak

Figure 2.4: Hydropower Types, The role of hydropower installations for sustainable energy development in Turkey and the world (Mehmet Bilgili, Harun Bilirgen b, Arif Ozbek a, Firat Ekinci c, Tugce Demirdelen)

In general hydropower plants vary in terms of the type and size of their generation unit or plant, their function (electricity generation, capacity or multi-purpose), their size, and the height of the water fall (head). Local conditions determine the design of of hydroelectric power plants. The most critical parameters in choosing a site specific hydraulic turbine, are the head and discharge pressures. The usage of very low head water resources is an innovative development in renewable-energy technologies mainly due to low environmental impact. Renewable energy sources have increasingly contributed to global electricity capacity every year.

There have been a great turn to hydroelectricity the recent years as a result of the carbon and fossil fuel exhaustion. It is a fact that in 2016, electricity from hydropower is the 71% of total renewable electricity and 16.4% from electricity produced from all the sources. This can be seen from the fact that total hydropower installed capacity worldwide is around 1.21 TW. Comparing the electricity generation of other renewables to that of hydropower between 2010 and 2016, we can easily notice that hydropower electricity generation is almost three times more efficient than that of other renewables.

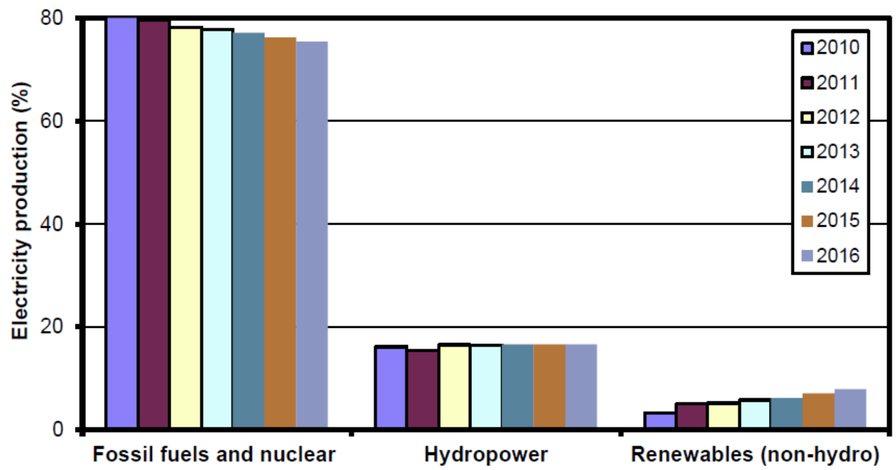

Figure 2.5: Electricity production in the world. Hydropower Types, The role of hydropower installations for sustainable energy development in Turkey and the world (Mehmet Bilgili, Harun Bilirgen b, Arif Ozbek a, Firat Ekinci c, Tugce Demirdelen)

2.4.1 Hydropower in Asia and Oceania

The hydro power plants with the most installed power are located in Asia , with power stations that have in installed capacity of 511 GW. Next is Eastern Asia with 381 GW. The rest of Asia are the Central and Southern and Southeast that produce 72.3GW and 57.8GW respectively. China, India and Japan are the countries with the most contribution in hydroelectricity production. While India and Japan produce 11.1 Mtoe and 7.85 Mtoe per year respectively, China has total installed capacity around 319GW and manages to produce 96.9 Mtoe per year, quantity that makes the bigger contributor worldwide in hydroelectric energy meaning that manages the one third of the total hydropower capacity. There have been great advance in the construction of pump-storage power plants in this country with total installed capacity of 23060 MW, the two biggest being in Guangzhou, being operational since 2000 and with capacity of 2400 MW, and Huizhou, operational since 2011 and capacity of 2400 MW. The other major power plants that use pumped-storage can be seen in Table 2.1.

The biggest hydroelectricity projects in China that dont use pumped-storage technology are the Three Gorges Dam, the Xiluodu Dam, the Xiangjiaba Dam and the Longtan. The Three Gorges Dam the largest water conservancy project in the world and uses the waters of the Yangze River. It has 26 units, started operating in 2008 and it has the huge number of capacity at 22500 MW. The Xiangjiaba Dam and the Xiluodu Dam reside next to Jinsha River and are considered to be in the largest hydroelectric power plants in the world and have respectivelly installed capacity of 6448 MW and 13860MW. The Longtan Dam, operating since 2009, consists of 9 units and has installed capacity of 6300 MW. These projects are considered to be a key factor in Chinas production of hydroelectricity. Moreover, Jingpin-I and Jingpin-II reside next to Yalong River and have installed capacity of 3600 MW and 4800

Name of the PHES plant	Installed capacity (MW)	Operating Date
Tianhungping	1836	1998
Liyang	1500	2017
Qingyuan	1280	2015
Hohhot	1224	2014
Shenzhen	1200	2017
Hongping	1200	2016
Tongbai	1200	2005
Xianyou	1200	2013
Bailianhe	1200	2009
Baoquan	1200	2011
Xilongchi	1200	2008
Pushihe	1200	2012

Table 2.1: Operational PHES plants in China

MW respectivelly. Finally, another great hydroelectric power plant in China is the Xiaowan, which was operated in 2010 and is able to produce 4200 MW.

In Asia, Japan despite not being able to match China, has a great contribution to the hydroelectric energy worldwide having facilities with total installed capacity of 49905 MW. The most of these use pump-storage technology and in total produce 27637MW. Japan invested a lot in the pump storage facilities in order to have them to provide energy for the nuclear plants. The biggest pump storage in Japan is in Kannagawa, which consists of two units that total 2820 MW and is the biggest in the whole country. This facility started in 2005 with 940 MW and in 2012 the second unit operated reaching total capacity of 2820 MW. The second biggest is in Okutataragi which operates since 1974 and has installed capacity of 1932 MW. The other major pumped storage power plants can be seen in the Table 2.2

Name of the PHES plant	Installed capacity (MW)	Operating Date
Okumino	1500	1995
Okochi	1280	1992
Shintakazegawa	1280	1979
Kazunogawa	1280	1999
Okuyoshino	1206	1978
Omarugawa	1200	2011
Matanogawa	1200	1992
Tamahara	1200	1982
Shintoyone	1125	1972

Table 2.2: Operational PHES plants in Japan

India has make great steps in harnessing the energy of the waters. There are hydropower plants in India with total installed capacity of 51494 MW , with 4786 MW regarding pumped-storage. The biggest facility in India that use pumped-storage technologies are the Sardar

Sarovar Dam with capacity of 1200 MW and operation date of 2005. Another big power plant is the Srisailam Left Bank, which started at 2000 and has installed capacity of 900 MW. The power stations of the National Hydroelectric Public Corporation have big contribution to the production of electricity and have total capacity of 4154.2 MW. They are 15 and are located in northern India. The Bharka Dam is one of the biggest power stations in northern India. It operates since 1963 and has total installed capacity of 2866.3 MW. Another hydroelectric power station that contributes significantly is the Nathpa Jhakri Dam that has total capacity of 1912 MW. Finally, the hydroelectric power stations in Maharashtra have a total capacity of 2406 MW.

There are other countries in Asia and Oceania that produce hydroelectricity. The most important are South Korea (6447 MW), Vietnam (15211 MW with 4 major power stations), Pakistan (7264 MW), Tajikistan (5190 MW), Iran (11.196 MW), Australia (8790 MW), New Zealand (5254 MW) and North Korea (5000 MW). In these countries there are many small hydroelectric power plants but there are also some that have a fair amount of installed capacity. There are 3 major in Iran, the Masjed-e-Soleiman power station (2000 MW), the Karun-1 (2000 MW) and the Karun-3 (2880 MW). Moreover, two notable are the Tarhela Dam (3480 MW) in Pakistan and the Hoa Binh power plant (1920 MW) in Vietnam. [3] [5] [7] [8] [9]

2.4.2 Hydropower in Europe

Nowadays, hydropower is a mature technology in Europe, with an estimated total installed capacity of 293 GW, specifically more than 150 GW represent storage and pumped-storage stations. Hydropower production in Europe reaches 70.8 Mtoe per year. Most of the hydropower potential rests in in northern Europe. The new projects in Europe have plans for pumped-storage, a hydroelectric technology with great potential (8600 MW planned or under construction). The majority of the operating pump-storage facilities are currently located in the Alpine countries (France, Switzerland and Austria and Germany). Facilities can, also, be located in Portugal and Spain. Investments aim to the refurbishment and modernization of existing facilities in order to minimize environmental impacts, improve efficiency, flexibility and system resilience. The development in Hydropower is supported at country-level by policies involving targets (e.g. hydro target in Turkey is 36 GW by 2023), feed-in tariffs, tax incentives/subsidies and power purchase agreements. According to International Hydropower Association, 2016 the top countries per installed capacity (together with pumped storage) include: Russia (50624 MW) Norway (30566 MW), Turkey (25886 MW), France (25397 MW), Italy (21880 MW), Spain (18561 MW), Sweden (16419 MW), Switzerland (15635 MW), Austria (13178 MW) and Germany (11258 MW). Moreover the countries with the most generating capacity are: Russia (160171 GWh), Norway (139000 GWh), Sweden (73927 GWh), Turkey (66900 GWh) and France (57300 GWh) (Figure 2.6). [29]

Russia is the leader in Europe per installed capacity in hydropower and also the leader concerning the most generating capacity. A great number of hydroelectric power plants are located in Russia. The most notable power plants depending on the installed capacity include: Sayano-Shushinskaya Dam and Hydroelectric Project Russia 6400 MW, Krasnoyarsk Dam 6000MW, Bratsk Dam 4000 MW, Ust-Ilimsk 4320 MW, Boguchany HPS (Hydroelectric Power Station) 2997 MW, Volgograd (Volzhskaya) Hydroelectric Power Station 2582 MW,

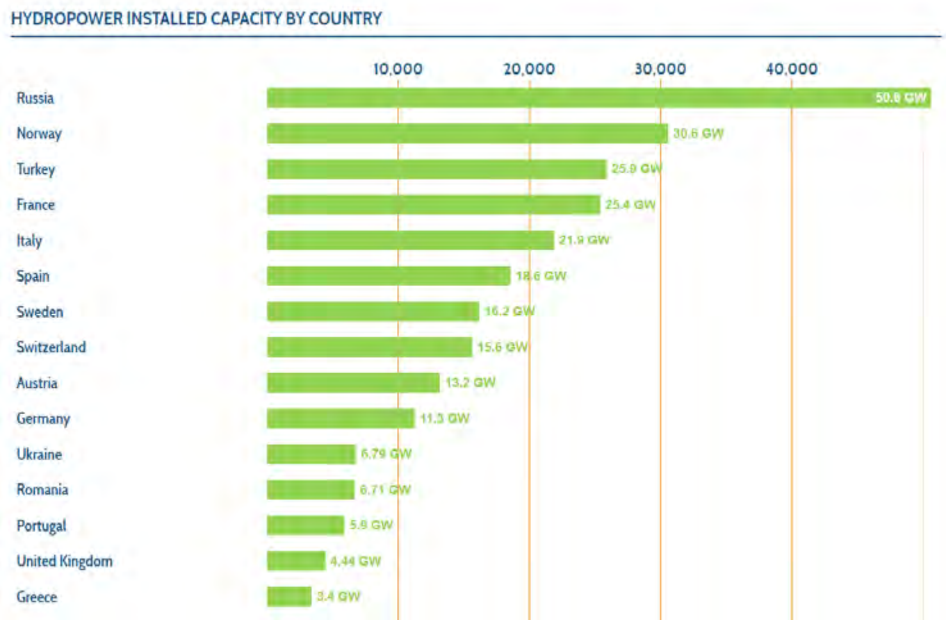

Figure 2.6: Hydropower installed capacity by country in Europe (World Energy Council)

Zhiguli HPS 2315 MW, Bureya (Bureyskaya) Hydroelectic Power Plant 2010 MW, Cheboksarskaya Hydroelectic Power Plant 1404 MW, Zaiskaya (Zeya) Hydroelectric Power Plant 1330 MW. As for Pump-Storage installations in Russia the biggest is Zagorsk I Pumped Storage Hydroelectric Power Plant Russia with installed capacity of 1200 MW. As far as concerned the rest of Europe hydropower there are some notable hydroelectric plants which appear in the following table (Table 2.3).

Name of the PHES plant	Installed capacity (MW)	Country
Ataturk HPS	2400	Turkey
Grande Dixene HPS	2069	Switzerland
Karakaya	1800	Turkey
Danipro HPP	1504	Ukraine
Keban	1330	Turkey
Inguri Dam HPS	1300	Georgia
Aldeadavila	1230	Spain
Iron Gate I	1166	Romania

Table 2.3: Hydropower plants in Europe

Moreover pump-storage technology has been penetrated in Europe. A huge number of pump-storage power plants operate in Europe. Some of the most notable pump-storage power plants in Europe can be seen in the table below (Table 2.4).

Name of the PHES plant	Installed capacity (MW)	Country
Grand Maison	1800	France
Dinorwig	1728	United Kingdom
La Muela de Cortes	1512	Spain
Vianden	1296	Luxemburg
COO I and II	1184	Belgium
Chiotas	1184	Italy
Goldisthal	1060	Germany
Markersbach	1050	Germany
Dnister PSP	1026	Ukraine
Ronco Valgrande	1016	Italy
Presenzano	1000	Italy
Limmern	1000	Switzerland

Table 2.4: PHES plants in Europe

2.4.3 Hydropower in Africa

Africa is a region with total installed capacity of hydropower of 25.3 GW and a total production of 8.56 Mtoe per year. The countries with the most hydroelectric generating capacity installed in the region are: Egypt (2800 MW), Ethiopia (2552 MW), Democratic Republic of the Congo (2495 MW), Zambia (2272 MW), South Africa (2251 MW, pumped storage 1580 MW), Sudan (2250 MW), Mozambique (2187 MW), Nigeria (2040 MW), Morocco (1770 MW, pumped storage 465 MW), Ghana (1584 MW). According to International Hydropower Association, 2016, Hydroelectricity generation in 2015 totaled 13.93 TWh in Zambia, 12 TWh in Mozambique, 9 TWh in Ethiopia, 8.67 TWh in Ghana, 6.31 TWh in Sudan, 5.90 TWh in Nigeria, 5.50 TWh in Zimbabwe and 4.41 TWh in Cameroon. Africa as region has a potential of 300 GW but only 8% has been exploited. Some of the most important projects that encourage regional interconnection and grid expansion are Ethiopias Gilgel Gibe III (1870 MW) and the Grand Ethiopian Renaissance Dam (6000 MW), as well as the Inga projects in DR Congo, where there is the possibility to install 40 GW in capacity. Guinea commissioned in 2015 three units at the 240 MW Kaleta plant. Mozambique has six hydropower stations in operations and two major projects in the pipeline: Mphanda Nkuwa (1500 MW) and the north bank expansion of the Cahora Bassa plant (1245 MW). Guinea commissioned in 2015 three units at the 240 MW Kaleta plant. Mozambique has six hydropower stations in operations and two major projects in the pipeline: Mphanda Nkuwa (1,500 MW) and the north bank expansion of the Cahora Bassa plant (1245 MW). Ethiopia plans to commission a further 3900 MW of new hydropower, including the 254 MW Genale Dawa 3 in 2016, and Geba I and II 385 MW in 2018. More projects include include Gibe IV and Gibe V (2000 MW and 600 MW, respectively), as well as the Upper Dabus (326 MW) and Halele Werabesa (436 MW). The country also plans to begin construction on a further 7,500 MW spread across ten projects by 2020. The biggest operational Pumped Storage power plants are located in South Africa Ingula and Drakensberg with generating capacity of 1332 MW and 1000 MW respectively and then STEP Afourer I and II in Morocco with generating capacity of 465MW. In Figure 2.7 installed capacity by country can be seen.[3] [9]

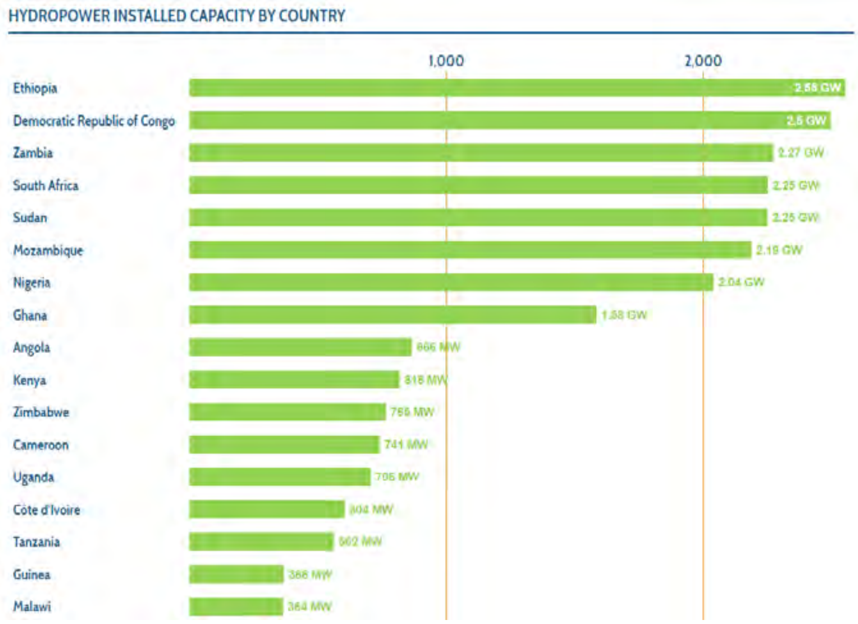

Figure 2.7: Hydropower installed capacity by country in Africa (World Energy Council)

2.4.4 Hydropower in North and Central America

This region has made many investments in the hydroelectricity and that can be seen from the fact that the two countries with the most contribution, US and Canada, are in the worlds leading countries in hydroelectricity. North America has total installed capacity of 193 GW and managed to produce 56.4 Mtoe in 2015.

According to IEA, Canadas 26% of total electricity comes from hydropower by having power plants with total installed capacity of 79202 MW. In Canada there is a project with 4 great stations in Romaine that will increase the total capacity by 1550 MW. From the installed facilities Canada is a country that relies a lot at hydroelectricity. The biggest is the Churchill Falls generating station with installed capacity of 5490 MW. Moreover, Canada has many other power plants that are great contributors to the production of hydroelectricity. These are:

- GM Shrum 2730 MW
- Revelstoke 2480 MW
- Mica Creek 1804 MW

- Limeston 1304 MW
- Sir Adam Becks 1500 MW
- La grande-1 1436 MW
- La grande-2 2106 MW
- La grande-3 2418 MW
- La grande-4 2779 MW

The United States is second only to China in terms of the generating capacity of its hydropower plants. US is one of the biggest contributors in hydroelectric energy by having facilities with 101755 MW installed capacity, with 22441 MW being pump storage. The period when the US made a serious turn and constructed many pumped storage facilities was between 1970-1985.

The biggest pump storage power plant in US is in Bath County with total installed capacity 3003 MW. This power plant operates since 1985. Another facility is in Ludington with 1872 MW capacity since 1973. Another major pumped storage power plan is the Raccoon Mountain with total installed capacity of 1652 MW and it started its operation in 1978. More about Raccoon Mountain will be analyzed in the next chapters. The rest pump storage power plants in the US can be seen in Table 2.5.

Name of the PHES plant	Installed capacity (MW)	Operating Date
Castaic	1556	1973
Helms	1212	1984
Blenheim Gilboa	1160	1973
Northfield Mountain	1124	1972
Rocky Mountain	1095	1995
Muddy Run	1072	1966

Table 2.5: Pump-Storage plants in the US

But US has major power plants that produce electricity with different methods than pump storage. The biggest in US and one of the biggest in the world is the Grand Coule with installed capacity of 6809 MW. There are many small hydroelectric power plants that contribute but there also a few that are large and are important in the production of hydroelectricity in the US. Some of these are:

- Robert Moses Niagara Dam 2525 MW
- Chief Joseph 2456.2 MW
- John Day power plant 2160 MW
- The Dalles 1819 MW
- Hoover Dam 1304 MW

- Rocky Reach 1279 MW
- Bonneville power plant 1092.9 MW
- Bountary Dam 1039 MW

Finally in central America the most notable country that contributes is Mexico with total power plant installed capacity of 12435 MW. The two major hydroelectric stations are the Manuel Moreno Torres station with 2430 MW and the Malpaso station with 1080 MW.[3] [9]

2.4.5 Hydropower in South America and Caribbean

South America is a region with a total installed capacity of hydropower 159 GW and an annual hydropower production of 61 Mtoe. The countries with the highest hydropower capacity installations in 2015 include Brazil (91650 MW, pumped storage 30), Venezuela (18486MW), Colombia (11392 MW), Argentina (10118 MW, pumped storage 974 MW), Paraguay (8810 MW), Chile (6622 MW), Peru (4190 MW), Ecuador (2297 MW) and Costa Rica (1800 MW). Total hydroelectricity output for the same year amounted to 382.06 TWh in Brazil, 79.56 TWh in Venezuela, 59.43 TWh in Paraguay, 49 TWh in Colombia, 41.46 in Argentina and 26.06 TWh in Peru. Total installed capacity in South America totalled in 2015 to 152813 MW and 1004 MW pumped storage, with electricity generation reaching 684 TWh. Moreover region has great potential for harnessing hydropower potential and more specifically an unexploited potential of 430 GW. Around 3.8 GW were added in total in South America in 2015, mainly coming from Brazil (2.4 GW), but also from countries such as Colombia (599 MW), Peru (370 MW) and Venezuela (257 MW). There are some very notable hydropower projects in Latin America. Some of them are:

- Brazil: Itaipu (14000 MW), Jirau dam (3750 MW), Santo Antnio (3568 MW), Teles Pires, Ferreira Gomes and other 52 stations totalling around 156 MW.
- Venezuela: Fabricio Ojeda (257 MW commissioned in 2015, total 771 MW) and Manuel Carlos Piar (2160 MW).
- Chile: the 19.2 MW Picoiqun run-of river plant and the 5.5 MW Los Hierros 2 plabnt in Colbn.
- Peru: Cheves station (172 MW), Machu Picchu 2 (102 MW) and Santa Teresa (98 MW).
- Ecuador: 60 MW Manduriacu plant, Coca Codo Sinclair (1500 MW), Sopladora (487 MW), Toachi Pilatn (253 MW), Minas San Francisco (275 MW) and MazarDudas (21 MW), further 2.8 GW of capacity are expected to be constructed in the coming years.
- Costa Rica: Torito station (50 MW).
- Nicaragua: first hydropower project commissioned in 40 years, the 17 MW Larreynaga storage project, which will generate an estimated 73 GWh per year.
- Panama: 32 MW Bonyic station.

As for Pumped Storage power plants the biggest is located in Argentina Rio Grande with a generating capacity of 750 MW, Los Reynos also located in Argentina with a generating capacity of 224 MW and Pedreira PSP in Brazil with a capacity of 20 MW. For power plants that are not with the pumped-storage technology, South America countries have made full exploitation of the waters they have. There lie large power plants that are considered to be in the largest worldwide. Some of the largest hydropower plants are presented in Table 2.6.[3] [9]

Name of the PHES plant	Installed capacity (MW)	Country
Yacyreta	3100	Argentina-Paraguay
Salto Grande	1890	Argentina-Uruguay
Piedra del Aguila	1400	Argentina
Guario	1213	Colombia
Guri	10025	Venezuela
Macagua	3125	Venezuela
Manuel Piar	2530	Venezuela
Caruachi	2160	Venezuela
Ilha Solteira	3444	Brazil
Xingu	3162	Brazil
Paulo Afonso IV	2642.4	Brazil
Itumbiara	2082	Brazil
Sao Simao	1710	Brazil
Bento Muntoz	1676	Brazil
Paulo Afonso Complex	1417.2	Brazil

Table 2.6: Hydropower plants in South America

Chapter 3

Reverse Pumped Hydro/Pumped-Storage

3.1 Pumped-Storage Technology

Pumped hydroelectric storage (PHES) is an energy storage system based on the technology of hydropower which is a well established and commercially-acceptable technology for utility scale electricity storage and has been used since as early as the 1890s. A typical hydropower plant with a dam and reservoir involves energy storage and more precisely water storage. There are mainly two kinds of pumped storage technologies. The main difference of these two kinds lies in the number of the reservoir that are used. The first way to use this technology involves one reservoir and the second two. In contrast with a convention hyropower plant, where a dam or a reservoir that store water during rainy seasons and release it during dryer, the pumped storage method has as main principle the production of electricity on a daily basis.

For this purpose, the natural flow of the water is not enough. During the periods with high energy demands, the upper reservoir releases the water to the lower reservoir through the turbines and provides electricity to the grid. Meanwhile during periods of low energy demands, the grid using spare electricity pumps the water from the lower reservoir back to the upper one, so that is available again for generation. Pumped storage plants usually use cheap or surplus electricity in order to pump and store water in the upper reservoir. This is the most cost-efficient way to produce electricity using the storage method. There are two main types of PHES facilities: (1) pure or off-stream PHES and (2) combined, hybrid, or pumpback PHES. The pure or off-steam PHES is based entirely on water that was previously pumped into an upper reservoir as the source of energy. The combined, hybrid or pumpback PHES use both the pumped water and the natural stream flow water in order to generate power. As far as concerned, the PHES are quite efficient. Older design facilities have a roundtrip efficiency (electricity generated divided by the electricity used to pump water) of 60% and lower, in contrast with the modern PHES systems which can achieve an efficiency of 80% and higher.

In general, Pumped storage technology is one of the most important and promising technologies and aids a lot in the advancement of the renewable energy. Pumped-Storage can be combined with the wind and create a hybrid form of renewable energy capable of producing fair amounts of energy. PHES according to researches from 2012 is the largest-capacity form of grid from the RES. [23] [24] [30] [37] [39]

3.1.1 Operation in Cycles of the PHES

The energy demand is the main factor that defines the operation of a PHES facility. Pure/off-stream pumped storage hydropower projects operate on a daily or weekly cycles. Projects operating on a daily basis use low-cost power at night in order to pump water to the upper reservoir. The time with the lowest demand, when low-cost energy is available, is considered to be from 10 pm to midnight to dawn around 6 pm. During the rest of the day, when is the peak of the energy demand, the facility generates energy. For plants that operate on a weekly cycle, the water is pumped to the upper reservoir during the night hours and on weekends because then is the lowest energy demands. Then during the active hours of the weekdays the water is released to the lower reservoir when the energy demands are higher. That way during the start of the week the upper reservoir is full and before weekend it is nearly empty. [21]

3.2 Efficiency of the PHES

The PHES projects, as mentioned, work in cycles. During the low demand the upper reservoir is pumped and during the high energy demands the water is released to the lower reservoir, where high value peak power is succeeded, and thus electricity is produced. This operation, naturally, has losses, which are caused from the friction of the pipes or from the turbine and pump efficiency. These losses cause the pumped storage plant to lose 20% - 30% of their initial power input. The improvement in cycle efficiency is important and the newest projects tend to do that, mainly due to the new turbine and pump technologies. For a new project the recommended cycle efficiency is around 75%.

There are some factors that affect the overall cycle efficiency of the project such as waterways and individual electrical-mechanical components. The efficiency values for a typical pumped storage hydropower project with single speed pump/turbine units are provided in Figure 3.1. According to the Table the majority of the losses so the lowest efficiencies are succeeded during the pumping and generating mode in the pump/turbine units.

One way to improve the efficiency is to have adjustable speed units instead of single speed when the plant operates in generating mode. The unit speed affect the turbine efficiency and therefore the losses are decreased. Both units in generating mode have a decline below 70% of the rated power output and for that reason the operators may restrict the pump/turbine unit operation so that they can obtain higher efficiency during generation mode and to prevent damage or unnecessary wear and tear on the machines.[21]

	Component	Indicative Value, %
Pump Cycle	Waterways	98.0-98.6
	Pump	90.0-92.0
	Motor	97.8-98.3
	Transformer	99.0-99.6
	Overall	85.4-88.8
Generating Cycle	Waterways	98.6-98.0
	Turbine	75.0-91.0
	Generator	97.8-98.3
	Transformer	99.0-99.6
	Overall	71.6-86.4
Operational	Losses & Leakage	98.0-99.8

Figure 3.1: Composition of Pumped Storage Hydropower Plant Cycle Efficiency For Typical Projects with Single Speed Pump/Turbine Units (Pumped Storage Hydropower: A Technical Review by Brandi A. Antal)

3.3 Historical Overview of Pump Storage Technology

PHES is not a new technology, the first PHES systems appeared in the alpine regions of Switzerland, Austria, and Italy in the 1890s. The earliest designs used separate pump impellers and turbine generators. Until 1950, the most facilities were located in Europe. The first pumped-storage facility in the United States was constructed in 1928, in Connecticut. In Asia, Japans first PHES was built in 1938 and Chinas was built in 1968. The main design for PHES was, since 1950, a single reversible pump turbine. Since then, many countries through the world had access to pumped-storage technology and built power plants. For the next decade, the development and progress of PHES was quite stagnant because many countries focus their funds and efforts in the development of the nuclear energy that seemed to be the case for the energy problem. As a result of this, many PHES facilities were supportive for the operation of nuclear power plants, for providing mainly peaking power. Low natural gas prices made gas turbine more competitive in providing peaking power than PHES and it was one of the main reasons for the downward trend in PHES in 1990s. As of 2014, the US Department of Energy (DOE) Global Energy Storage Database recorded over 300 operating PHES stations with a total capacity of 142 GW in 41 countries. National policies influence the regulations and financing of PHES. Japan, China and the United States have the largest PHES capacities in the world.

Pumped-Storage technology has bloomed in Japan and its facilities are the main contributors of hydroelectricity. Japan has steadily supported PHES through the years. The Japanese power sector is mainly composed of vertically integrated regional electric power utilities, which build, own, and operate the PHES facilities. The result of this is the creation of a stable and predictable financial environment that is friendly to new investments from both Japan and the rest of the world. The development of the PHES in Japan is intact connected to the development worldwide. The first PHES in Japan, as mentioned above, was built in 1938 and until 1960 the power plants were rare and small. But since then, Japan started a rapid advance in the PHES until 1990s. Since 1970, pure/off steam PHES has become the main design due to the ecological problems that were created from the hybrid systems. Nowadays Japan is the leader in PHES technology worldwide and has also invested in employing seawater PHES and variable-speed PHES. China is a rising power in PHES deployment. China is going to overtake Japan as host of the largest PHES capacities in the world, as China has a lot of facilities of PHES projects and under construction. New facilities in China are of large capacity and off-stream designs. Before 2004 most PHES facilities in China were constructed by local governments and local grid companies with diverse pricing models. In 2002, China restructured its power sector by separating them into two state-owned grid companies and five power generation corporations. A regulation by the National Development and Reform Commission in 2004 specified that PHES stations are transmission facilities and should be constructed and managed by the grid companies, and that the construction and operation costs of PHES should be incorporated into the operation costs of the grid companies.

As for United States most facilities were constructed in the 1970's and 1980's and then in the decade of 1990 the construction of PHES facilities slowed down due to environmental concerns. Many projects were canceled in combination with the environmental concerns and the power sector restructure. More specifically, during the 1990's the United States started to restructure the power sector by separating generation from transmission. A PHES facility usually cannot qualify as a power generator, because the net electricity output is negative. Although their crucial load-balancing and ancillary services to the grid reduce the need for transmission upgrades, PHES facilities are not recognized as parts of the transmission infrastructure. The development of PHES in the United States was discouraged due to this confusion in business models.

Finally the diverging paths of PHES development in Japan, China, and the United States prove that national regulatory and institutional environment affect directly with tremendous impacts on the development of PHES. PHES facilities require huge upfront capital investments, and paybacks are spread over many decades. A stable and predictable regulatory environment and a reasonable pricing scheme that allows PHES facilities to be compensated for their services to the transmission grid, must be provided by governments which aim to exploit the PHES development. [23] [24] [30] [37] [39]

3.4 Analysis of Turbine Technology

Nowadays the trend in the hydropower projects is about reversible turbines. As a result of this more and more hydropower projects use reversible pump/turbine and motor/generators assemblies which function both as a pump and as a turbine. There are two types of turbines that are used for pump storage, the single speed and the adjustable speed. The PHES facilities in majority use single speed turbines, because the concept of the adjustable speed turbines is relatively new and the plants are built many years ago, especially in the US. In contrast, new hydropower plants, especially in Japan, use adjustable speed turbines due to the fact that is more effective and there are many new projects that are about to use that kind of technology. Despite the effectiveness of adjustable speed technology, the cost of replacing an existing single speed turbine unit is high combined with with the increased powerhouse size. [27] [21] [34]

3.4.1 Turbines Configuration

In hydropower projects two are the main configurations for the operation of the project, with a separate pump and a separate turbine and another one when the pump and turbine operate together and are combined as one. The transition time between pumping and generating mode is shorter with a separate turbine and pump, with the drawback of a larger and more complex powerhouse and the usage of supplementary electrical-mechanical equipment. As a result of this the cost of the configuration and in general for the project increases. Unlike combined pump/turbines configuration is clearly smaller and electrical-mechanical equipment has a lower cost. In contrast with the lower cost and the smaller configuration the transition time between pumping and generating mode is longer due to the fact that turbine blade has to stop in order to change rotational direction and operate in the other mode (pumping to generating mode or the opposite). The new pump storage plants rely on combined pump/turbine for their operation and the older on separate pump and separate generator. [21] [27] [34]

3.4.2 Single Speed Turbines

As mentioned earlier, single speed turbines are used in the majority of the pump storage facilities. These turbines make practical and effective use of a synchronous electrical machine. This machine can be operated for both pumping and generating mode by just changing the rotation of the motor. In this type of turbine, the pumping happens at a synchronous speed and the opening of the wicket gate is nearly stable. In general in pumping mode, power input is depended and is inversely proportional to the head which affects the discharge. As for the single speed units, they cannot adjust the frequency because they are directly connected to the power grid and function at a given speed and power input. During generating mode the reversible pump/turbine is responsible for the handle of the the single-speed synchronous generator, for the electricity supply to the grid/system and the general regulations in the system. Wicked gates positions during the generating mode are modified by the operators in order to change the discharge. In addition, single-speed units operate within 70-100% of the pump/turbine maximum capacity. This happens for the maintenance of the optimal efficiency. For example, a 500 MW unit is under operation within a range of 400-500 MW. This unit flexibility makes possible for the operator to adapt the load demands of the power grid. [21] [27] [34]

3.4.3 Adjustable/Variable Speed Turbines

Despite hydropower being a quite mature way to produce electricity, the concept of the adjustable speed turbines is relatively new. The main characteristic of the adjustable or variable speed turbines is that the static frequency converters are used to control the rotation speed of the blades, providing that way a flexibility and a greater adaption in the power grid. The increased level of operating flexibility of these turbines make these type of turbines the main factor for the stability of electrical power networks. More specifically for small machines under 50 MW, with the help of a static frequency converter a synchronous generator is connected to the power grid. For units above 50 MW, double fed induction machines (DFIM) with a static frequency converter feeding the rotor makes the usage of adjustable speed turbines possible. The doubly fed induction machine (DFIM) has a three phase sinusoidal rotor voltage and current, which is supplied by an AC/DC/AC sold state converter. The frequency of the rotors voltage and current is adjusted in order to control the speed of the rotor. The DFIM technology is responsible for the creation of a rotating field on the rotor which helps in the operation of the machine in a fixed speed range around the synchronous speed at a fixed frequency. In order to have optimal efficiencies for these type of turbines, operators operate variable speed units between 70-100% of the pump/turbine unit maximum capacity.

The innovation in this technology is the rotor design, which consists of three main parts the slip rings, the overhang retaining system and the rotor rim. The slip rings supply the rotor with three phased current, slip ring per phase and usually one slip ring for the star point are needed. The frequency, at the beginning, starts increasing gradually and reaches the grids frequency during the end of the process. The Winding overhang of the rotor is a support system, which is subject to strong centrifugal forces during operation in order to avoid deformational and damages when the machine speed reaches runaway speed during load rejection. There are three concepts of winding overhang. The first concept uses a forged nonmagnetic steel cap which has the ability to withstand forces. In the second concept the overhang is covered by a steel or synthetic wire or a synthetic foil. As for the third concept the winding overhang is connected to the rotor rim through a set of retaining bolts. Finally, the last component is the rotor rim, which has similar role to the winding overhang. The rim is a part of an induction machine so it is exposed to magnetic fields.

The operation of the variable speed turbine systems in generating mode is similar to the operation of the single speed turbines. The position of wicket gates minimizes the losses and throttling effect. During pumping mode wicket gates are not throttling because this effect could cause additional losses, extra vibrations and damages on the mechanical equipment. Moreover, input power is adjusted due to operational speed ranges in order to avoid reverse flow in high heads and cavitation at low heads. In addition operational ranges make possible the control of the electrical power frequency on the power grid. [21] [27] [34]

3.4.4 Adjustable Speed Turbines Benefits

Variable speed turbines present some important advantages as opposed to single-speed turbines. As mentioned, the main difference of these technologies is the speed. Single speed have a stable speed, while adjustable speed allows the operator to control the speed and adjust it to the grid needs. The operation in speed ranges can result in better efficiency level at operating points not only during generation mode but also during pumping mode (Figure 3.2).

Variable speed technology turbines in pumping mode, at fixed head the power absorbed is able to change subsequently, permitting the grid frequency to be regulated. This range can be up to around 30% of the absorbed power. Operation mode is extended, in contrast with fixed speed units where their power can be regulated in generation mode and its power is constant/fixed in pumping mode (Figure 3.3).

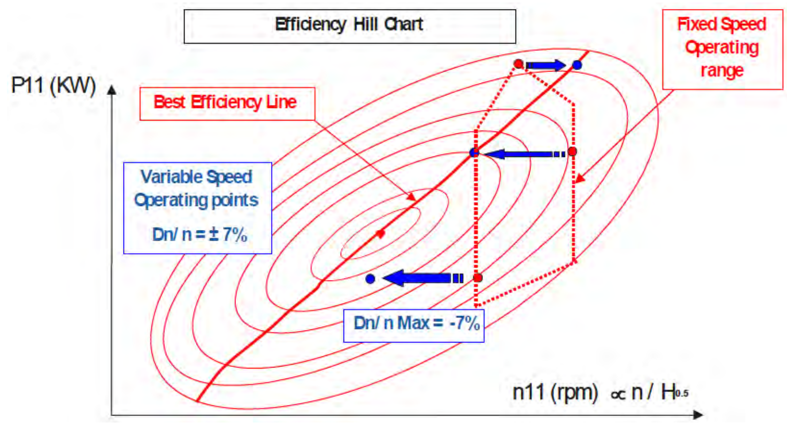

Figure 3.2: Operating points in turbine regime for fix speed red and variable speed blue: efficiency optimization (Gabriel Dan CIOCAN, Olivier TELLER, Francois CZERWINSKI)

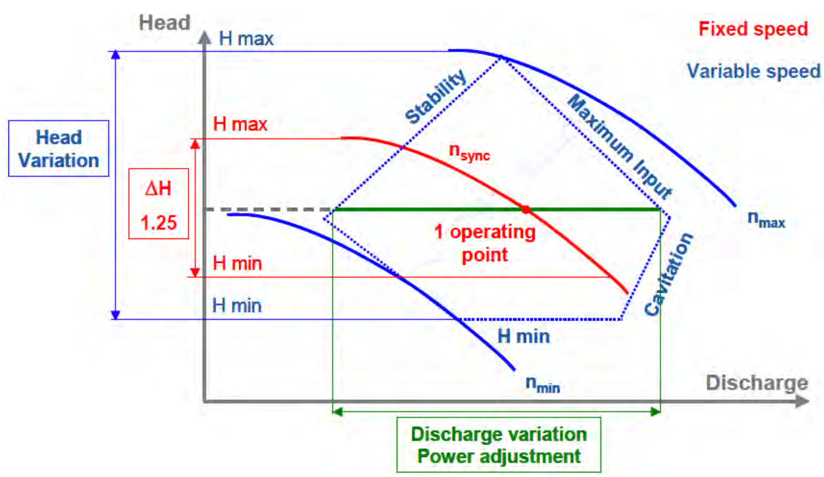

Figure 3.3: Operating domain for fix speed red and variable speed blue: grid frequency regulation (Gabriel Dan CIOCAN, Olivier TELLER, Francois CZERWINSKI)

In addition a more dynamically setting of the power thanks to flywheel effect is succeeded at variable speed units. For single speed, changes in power can only be possible through the adjustments of the discharge. In contrast as for the adjustable speed units, adaptations for the electrical machines are faster on the new requirements and compensate the inertia of hydraulic system. The variation of the operating point results in the optimization of the electrical and hydraulic parameters.

During pumping mode, adjustable speed turbines can operate with a part of the total load. That way they can correspond better to the grid needs. With this operation, a major problem in the pumping mode], the frequent machine starts and stops of the turbine is solved (Figure 3.4). That way the grid works better because the disturbances are minimized. Additionally, with this adjustment variable speed turbines makes it possible to combine the production of hydropower with another renewable energy source.

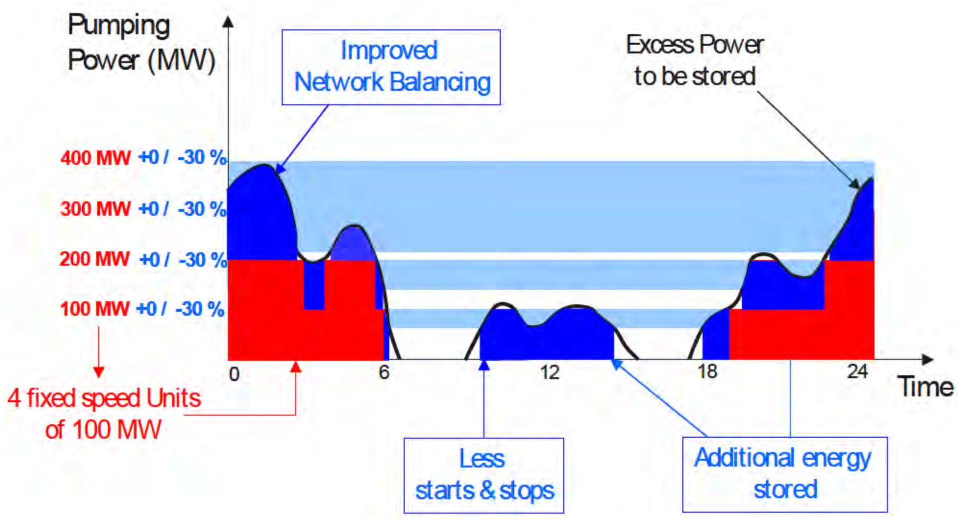

Figure 3.4: Operation of fix speed red and variable speed blue power plant (Gabriel Dan CIOCAN, Olivier TELLER, Francois CZERWINSKI)

Finally extension of the operating range increased cycling efficiencies which result in higher flexibility to the grid is an example of the technical and economic advantages that adjustable speed technology offers.[21] [27] [34]

3.5 Design characteristics and concepts of Pump Storage

3.5.1 Upper and Lower Reservoir

The design of the reservoirs depends on some crucial factors. If an existing reservoir is available, this reservoir or these reservoirs can be used. As a result of this the construction cost is reduced and may provide a reliable water source. Another factor is the existence of rivers and streams and the topography of the project site which determine the layout of the reservoirs. If there are favorable geologic conditions,a dam on a mountain can be constructed and another possible location for the construction of the dam is valley. Moreover geologic conditions play an important role and have a great impact on the selection of the location of potential reservoirs and their design. The rapid change in the levels of water in both the upper and the lower reservoir during the operation of pumping and turbine can have a great impact on the stability of the reservoir slopes, consequently lining of the reservoir may be required. Finally another concern is related to the water floods in the reservoir foundations which may require a grout curtain or lining of the reservoir. In closed-system pumped storage is of a great importance because conservation of water is a main factor in these systems.

For the correct selection of the reservoir, the size of the installed units, the operation head, the site characteristics and the turbine operation time are required. The most common operation hours for a pump storage plant are 4 to 20 hours. That way it is cost beneficial. There is a simplified equation that can help in calculating the appropriate storage of the reservoir. [21] The given formula is:

$$S = \frac{(2.6 \times C \times t)}{(H \times eg)} \tag{3.1}$$

In Formula 3.1 :
S is the storage of the reservoir (m^3).
C is the plant capacity (MW).
t is Storage requirement in hours of equivalent full-load generation .(hours)
H is Average gross head (m).
eg is generation efficiency, including head losses (%).

3.5.2 Surface reservoir pumped storage hydroelectric storage.

All existing pumped storage projects in the world involve surface reservoirs, either natural or artificial, and a small number that use very large water bodies. As we mentioned earlier, there are two types of surface reservoirs that can be used in PHES. The specific concept makes use of either natural or artificial surface water bodies such as rivers, lakes or seas. As a result of this we classify pumped-storage systems as Closed-loop or Open-loop system. Open-loop systems involve a reservoir and make use of the natural flowing water feature (e.g. river or sea). In contrast with open-loop, closed-loop PHES are not continuously connected to a natural flowing water feature. The main concept of closed-loop scheme involves two reservoirs that are isolated from a free flowing water source. The reservoirs can be natural or artificial. The closed-loop has fewer environmental impacts and less aquatic issues, like destroying the fish passages or causing trouble in the sediment migration, due to the fact that, after the initial filling of the reservoir, the only water transfer is the potential need for evaporation make-up water without the existence of other free flowing water source. [2]

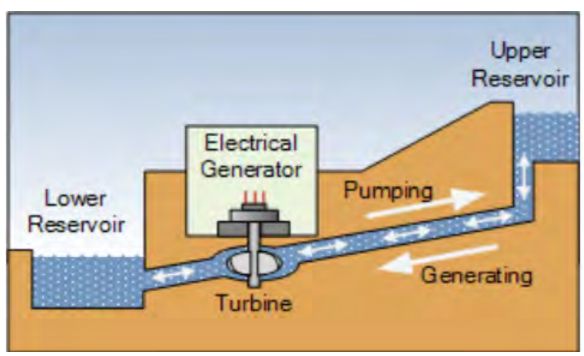

Figure 3.5: Surface pumped storage hydroelectric power (AET, 2017)

3.5.3 Sub-Surface Pumped Hydroelectric Storage

As we have noticed, PHES involves two reservoir, a lower and an upper. The lower is in many occasions a lake, a river or even an ocean. Another concept of PHES is the Sub-Surface PHES which has as a main feature a lower reservoir under the surface. While it is still a project that is yet to be used, it has great potential and minimizes a lot the environmental impacts, due to their site availability.

Abandoned mines, caverns, and man-made storage reservoirs are considered to be great (lower) reservoir options and already are under construction several projects of this concept. The finances of this concept could be difficult due to the underground excavation or materials-handling costs, construction risk, time required for underground excavation and construction. The existing sub-surface structures are targets for potential underground reservoirs because there is no excavation cost. Moreover, the cost can be further reduced through the sale of excavated materials, like ores. [2]

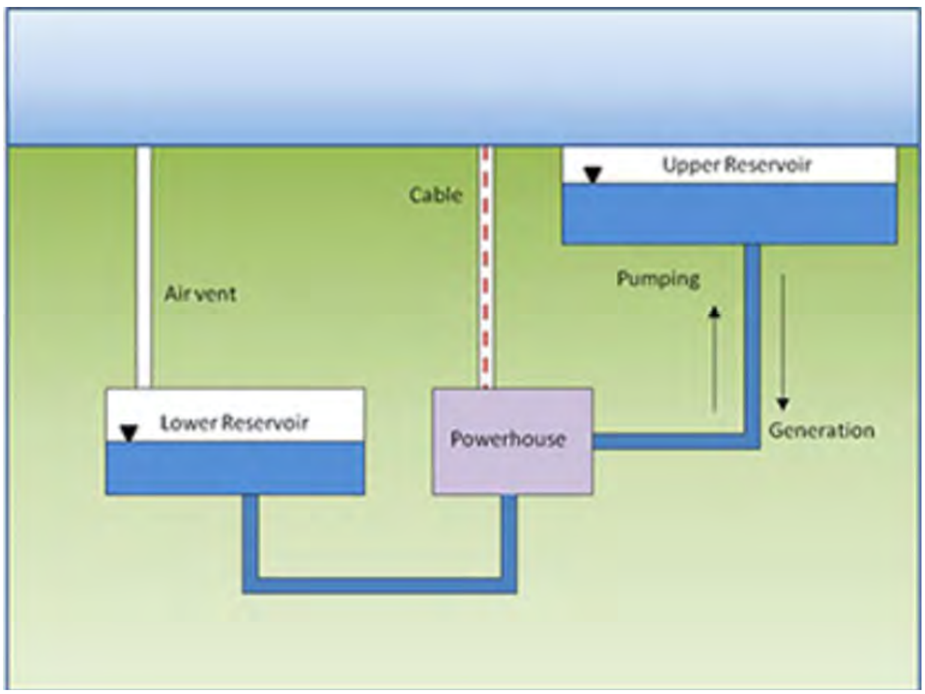

Figure 3.6: Sub-surface pumped hydroelectric storage (ESA, 2017)

3.5.4 Head

Head is another important factor for a PHES project. Low head projects are more expensive because they require larger pipes. High head projects (typically over 762m) require more complex pump/turbine units and the ability of regulation of the units in generating mode is eliminated. High head projects are more cost effective, because the total energy stored is proportional to the product of volume of water stored by the total head. As a result of this a high head project would require smaller reservoirs smaller electrical and mechanical equipment producing an equal amount of energy. Typically case studies have shown that heads range between 362m to 429m. [21]

3.5.5 Water Flow Rate

The water flow rate is a very important factor in the operation of the PHES. There are two main parameters that determine the flow rate of the water, the desired generating capacity and the available head. Moreover, the design of the flow rate depends from the pump/turbines units and the waterways. The higher the flow rate the larger the pump/turbines and the waterway pipes. Additionally, another consideration we need to take when calculating the flow rate is the head losses in the waterways, which are very important. Smaller flow rates in smaller pipe diameter have higher head losses than those in larger pipes, although larger pipes are more expensive. [21]

3.5.6 Water Ways

Another great factor for the design of PHES project is the waterways. It plays a very crucial role for the overall project because it directly affects the efficiency of the facility and the performance of the pump/turbine units. For PHES projects waterways are the main link between the upper reservoir, the powerhouse and the lower reservoir. Based on the hydraulics of the system, some projects may also require a surge tank to protect the waterway and pump/turbine units from water hammer. In general PHES have two segments of waterways. The first segment is the high head portion between the upper reservoir and the pump/turbine unit(s) and the second section is the low head portion between the pump/turbine unit(s) and the lower reservoir.

For the optimal operation and the lower cost the water way must be the shortest distance between the lower and the upper reservoir. The shortest distance for the water way contributes in the operation because it minimizes the losses due to friction both in pumping and in generating mode. The topological and the geographical characteristics of the site play a major role in the water way configuration. The waterways can be on the surface or underground. The materials used for their creation include steel and concrete and for underground waterways may additionally be constructed at tunnels in hard rock. [21]

3.5.7 Design Parameters for Pump Turbine

There are three main factors that determine the velocity of rotation of the turbine, the rated output of the turbine during the operation, the corresponding rated head and the turbine specific speed. More specifically the speed of rotation can be calculated according to the formula below:

$$N_s = \frac{N \times \sqrt{P \times 1.358}}{(H^5/4)} \tag{3.2}$$

In Formula 3.2:
N_s is the specific speed of pump turbine when operating in pumping mode.
N is the rated speed in rev/min.
P is the turbine output in kW.

H is the rated head in meters.

The specific speed value defines the approximate head range application for turbine type and size. Low head units tend to have a high specific speed and high-head units to have a low specific speed. The pump input at rated head in kW and the specific speed are obtained from the formula:

$$P = 9.8 \times Q \times H \times E \tag{3.3}$$

In Formula 3.3:
E is the Pumping efficiency.
Q is the discharge m^3 / s.
H is the rated head in meters.

The pump specific speed is calculated from the formula:

$$N_q = \frac{N \times \sqrt{Q}}{H^{\frac{3}{4}}} \tag{3.4}$$

In Formula 3.4:
N_q is the specific speed of pump turbine when operating in pumping mode.
N is the rated speed in rev/min.
Q is the discharge m^3 / s.
H is the rated dynamic head in meters.

The net head available to the turbine and unit size dictates the selection of type of turbine suitable for use at a particular site. The term specific speed is generally used in classifying types of turbines and characteristics within type as shown in Figure 3.7 below.
Relationship between head and specific speed for preliminary selection of turbine types as per Indian Standard 12837 is given in figure below:
The maximum pump capacity is calculated according to formula 3.5.

$$P_{max} = P \times (1 + (\lambda \times \frac{\Delta H}{H}) \tag{3.5}$$

In Formula 3.5:
P is the Pump input.
Δ H is the Maximum dynamic head design dynamic head.
λ is the Relative capacity variation.
H is the Dynamic pumping head. [38]

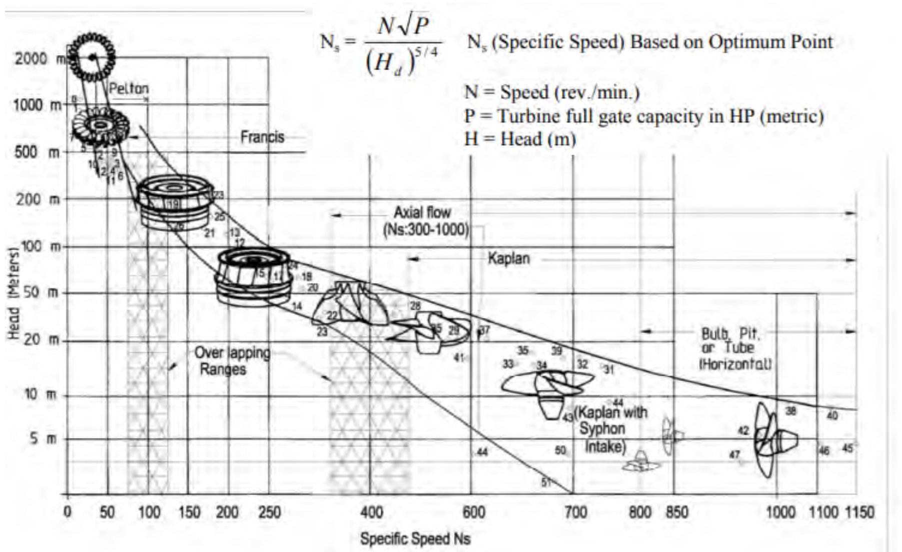

Figure 3.7: This figure shows the various turbine type as a function of specific speed (N_s) and head. This figure should be used a guideline, as there is overlap between the various turbine types with respect to their operating ranges. [38]

3.5.8 Requirements of selection for Hydro Turbine above PHES plant above 5 MW

For the appropriate selection of the turbine there a eight factors that need to be taken into account:

1. Available head
2. Turbine Efficiency
3. Speed in rpm
4. Cavitataion and plant setting
5. Part load operation
6. Runaway speed
7. Runner diameter

Selection of turbines for a site is determined by trial and error process and in consultation with manufacturers for optimum determination of the type, size, setting and efficiency. Setting of a turbine knowing the minimum tail water level requires cavitational considerations. Different types of turbines have different cavitation coefficients. For example, Francis turbine coefficient is less than that for Kaplan. That means that Francis turbine requires less submerging or excavation than Kaplan and furthermore costs less, concerning excavation costs. Also, a factor that determines the cavitation is the speed that is needed. Higher speed requires lower placement of the turbine. Cavitation results from sub-atmospheric pressure at places on runner and runner chamber. To diminish this problem the turbine runner is placed at depths below

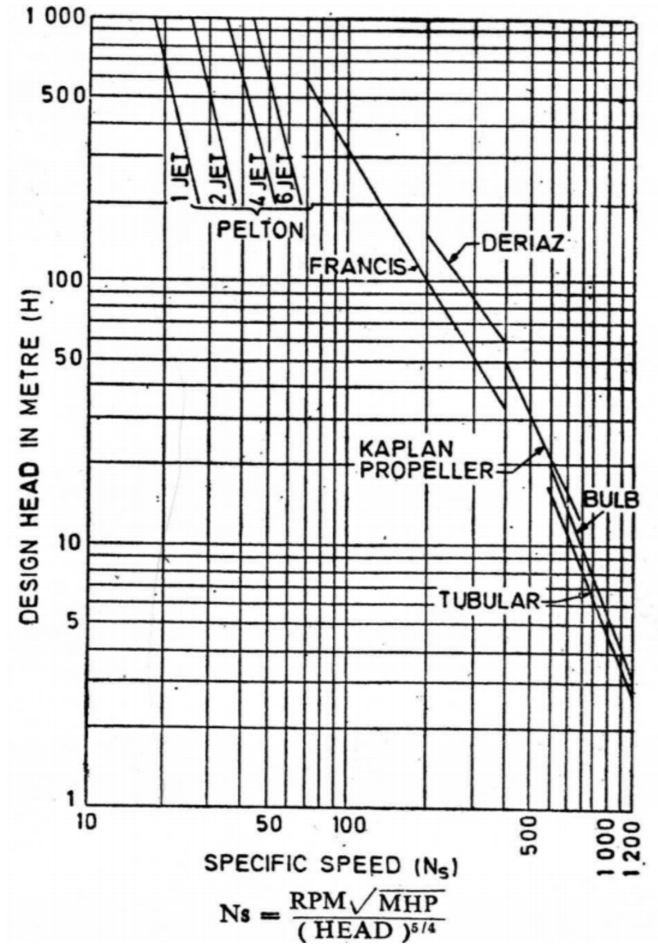

Figure 3.8: Relationship between Head and Specific Speed [38]

the minimum tail water to obtain a countering pressure. The appropriate value of the depth of setting for runner of different specific speed is computed using a cavitation coefficient for the particular specific speed, as it is seen in formula 3.6

$$Z = (Ha - Hv) - \sigma \times H \tag{3.6}$$

In Formula 3.6:
Z = Depth of centre line of runner below minimum level of tail water.
Ha = Atmospheric pressure in meter (m) water column at plant elevation.
Hv = Vapor pressure in meters at plant location temperature.
H = head on turbine, meters.
σ = Plant sigma or cavitation coefficient for the turbine specific speed.

The value for σ for selection purposes may be found from the expression which is as follows (IS: 12800):

$$\sigma = \frac{n_s^{1.64}}{50327} \tag{3.7}$$

In Formula 3.7:

n_s is the curves of the turbine.

The design Parameter for motor generator is given by number of pair of poles and it is determined by:

$$P = \frac{60 \times f}{n} \tag{3.8}$$

Where in Formula 3.8:
P= number of pairs of poles.
f= frequency in cycles per second.
n= rated speed of machine in rev/min. [38]

3.5.9 Generator and Pump classifications

Every pumped storage hydro plant has different configurations for both the pump and the generator. We have 3 categories of these classifications which are: Binary set, Ternary set, Quaternary set.

Binary Set: This set consists of a pump-turbine and one electrical machine (motor/generator). During generating mode the set rotates in one direction.In contrast, during pumping mode, it rotates in the opposite direction. Heads ranges from 10 m to 70 m, the single stage turbines can be used while the multi stage pump turbines can be used for heads from 700 m to 1200 m. This set is the most common choice due to the cost efficiency as regards to installation, maintenance and operation. [16]

Ternary Set: This configuration set consists of a motor/generator, a turbine and a pump all in the same shaft. In this set the turbine and the generator work together towards the same direction. [16]

Quaternary set: In this set the turbine and the pumps are not together in the same shaft and for that reasons two powerhouses are needed. One powerhouse is for the pumps and one for the turbine. That means that two reservoirs are connected by two different penstocks, one for generating and one for pumping. [16]

3.5.10 The Air Cushion Chamber

The air cushion chamber is surged and is used to deplete the pressure that is result of the rapid valve closure in pipes connected to the reservoirs. The kinetic energy of the moving water the energy stored in the liquid and pipes creates the pressure.

Regarding the design of the air cushion chamber, we use the Laplace law because the pressure energy is transferred only as work and there is no heat losses or matter between the system and its surroundings (Formula 3.9).

$$P \times V^{\gamma} = constant \tag{3.9}$$

Where in Formula 3.9:
P is the pressure inside the air cushion chamber (Pa / bar / atm).
V is the volume of the air (m^3).
$\gamma = C_p/C_v$.
where C_p and C_v are the constants of pressure and volume respectively.

The area of the surge chamber can be determined from Formula 3.10:

$$A_{eq} = \frac{1}{\frac{1}{A_{ac}} + \gamma \times \frac{h_p}{V_o}} \tag{3.10}$$

Where in Formula 3.10:
A_{ac} is the area of the air cushion chamber (m^2).
V_o is the starting volume and can be calculating as $V_o = A_{ac} \times H_{oac}$.
H_{oac} is the starting height.
h_p is the pressure inside the chamber by Bernoulli equation. [16]

3.5.11 Design Parameters for the Power Plant

The size of erection bay in combination with the overall dimensions of the turbine, draft tube, scroll case and generator including the number of units in a power station determine the design of the power plant.

Length of Power Station The length of the power plant is affected by the number of the units, the space required for the crane to handle the last unit and the space of the erection bay. The length can be determined by the Formula below:

$$L = N_o \times (unitspacing) + L_s + K \tag{3.11}$$

In Formula 3.11:
N_o is the number of units.
L_s is the length of erection bay.
K is the space required for the crane to handle the last unit depending on the number and size of the crane which is usually 3.0 5.0m. [16]

Width of Power Station: The width of the power plant is mostly for the machines. The overall dimensions of the spiral casing and the hydro generator may be chosen with respect to the vertical axis of the machine. There will be a clearance of about 1.5 to 2.0 m for concrete upstream of scroll case. Also for the approaching of the draft tube there is a 1.5m to 2.0m space. If the main inlet valve is within the power house there has to be plans so that all the types of the valves can fit within, such as the conventional butterfly, spherical or pressure relief valves. There must also exist a provision for the collateral equipment and machines. [16]

Height of Power Station: The height of power station is the sum of the height from the bottom of the draft tube to the center line of the spiral casing and the height from the center line of the spiral casing to the top of the generator. The second height can be calculated as: [16]

$$H = L_T + h_j + K \tag{3.12}$$

In formula 3.12:
L_T is the length of stator frame.
h_j is the height of load bearing bracket.
K is the constant ranging from 5.5 to 5.0 m depending on the size of the machine.

3.5.12 Parameters and characteristics of a Pumped Storage Plant Construction Site

As mentioned, the PHES consists mainly of two reservoirs, an upper and a lower, a powerhouse which contains hydropower electrical mechanical equipment and a transmission connection to the power grid. The most common operation low-cost electricity is used to pump water from the lower to the upper reservoir and water stored in the upper reservoir is then released during high energy demand periods. For the operation of a PHES facility there are technical specifications that need to be met:

- Topographic conditions that demand an sufficient height difference between the lower and the upper reservoir. The larger the difference the more the energy that is going to be produced.
- Low cost power and access to electrical transmission network.
- There must be plenty of water and an adequate water flow, because the larger the water quantity is the more the energy that is produced.
- Good geological and technical Conditions.

Addition key attributes to make the facility to be more productive and is:

- Exploitation of an existing reservoir for the upper or lower reservoir (which will lower the initial cost).
- Topographic conditions that enable the shortest and fastest route for the water flow.
- Favorable Head for installation of smaller turbine/pump units [21]

In general, the selection of a PHES site is a crucial issue, because it has to be feasible, commercially and socially acceptable. Feasible sites must be always researched in order to find more accurate, simple and affordable technology for most precise selection of these sites. Moreover, through the passage of time the finding of feasible sites which meet the economic and technical specifications are very rare. [37]

3.6 Operation of the PHES

As mentioned, the two main operations of the pump storage is the pumping and the generating mode. Each mode is used depending on the energy demand. When the energy demand is high the facility operates with the generating mode, in which the upper reservoir is emptied in the lower and electricity is produced. When the energy demand is low, the pumping mode operates. In this, the water moves with the help of the turbines to the upper reservoir and excess energy is used.

3.6.1 Pumping Mode

In pumping mode there is a number of factors which determine whether water will be pumped to the upper reservoir at each time step. There are four main factors that dictate whether energy is available and if so, what quantity of energy is available for pumping. The factors are:

1. Available Excess Energy, is related to the existence of the excess energy in the power grid and the quantity of excess energy that is available for pumping.
2. Unit Capability, the capacity of the pump/turbine units. The model considers single-speed and adjustable speed pumps separately.
3. Water Available in Lower Reservoir, the quantity of water available in the lower reservoir.
4. Volume Available in Upper Reservoir, volume of water that is available in the upper reservoir. At each time e step water can only be pumped if there is space available in the upper reservoir.

Available Excess Energy was calculated using the following power equations:

$$E_{pump} = P_{pump} * t \tag{3.13}$$

In formula 3.13:
E is the energy of the pump. P the power of the pump.

$$P_{pump} = \frac{\gamma \times Q \times \Delta H}{\eta} \tag{3.14}$$

In formula 3.14:
if we solve for Q, we have the Available Excess Energy (Formula 3.15).

$$Q = \frac{P_{pump} \times \eta}{\gamma \times \Delta H} \tag{3.15}$$

In Formula 3.15:
Q is the Available Excess Energy.

η is the pumping efficiency (usually around 98%).
ΔH is the net head in meters.
P_{pump} is the power of the pump in Watts.
γ is the specific weight of water at 4 °C is is 9807 kg/ (m^2/s^2)

The Unit Capability is calculated differently in single speed units and in variable speed units. In single speed units, during pumping mode, the power input is stable. While discharge is different based on pumping head the model assumes constant head therefore discharge is also considered to be constant for single speed units and each single speed unit is calculated separately. For each unit, the flow (Q) is calculated separately using the upper model (Formula 3.15). The adjustable speed units have a range of power inputs. In order to to calculate the flow (Q) the equation (Formula 3.15) is used.

The Water Available in Lower Reservoir is calculated based on the water rise in the lower reservoir. For each 1 hour time step, the volume of water available (V) in the lower reservoir and for time t using the Formula 3.16.

$$V = Q \times t \tag{3.16}$$

Solving for Q we have Formula 3.17

$$Q = \frac{V}{t} \tag{3.17}$$

Q is in m^3.

The Volume Available in the Upper Reservoir at each time step is calculated based on the elevation of the upper reservoir at the end of each step. Then the flow is calculated with the 3.16 formula and 3.17. The model selects the minimum flow value available for generating at each time step, then evaluates whether there is Volume Available in Lower Reservoir. Now that each flow (Q) is known, the minimum is used in order to calculate the energy of the pumping (E_{pump}) can be calculated with the Formulas 3.13 and 3.14 and the volume (V) with the Formula 3.16.

Example: Consider a situation where flow available is Q = 112.871 m^3/s , pumping efficiency η = 98% , the net head is ΔH = 442.66 m, the time period = 3600 s, power is 500 MWh. Using equation from Formula 3.16, we are able to calculate the Volume.

V = $Q \times t$ = 112.871×3600 = 406335.6 m^3 is the volume of water to be pumped in the upper reservoir. Using Formula 3.14 P_{pump} is calculated:
P_{pump} = ($\gamma \times Q \times \Delta H$) / η = 9807 × 112.871×442.6 / 0.98 = 499.6 MW
E_{pump} = $499.6 \times 1hour$ = 499.6 MWh, using Formula 3.13. [21]

3.6.2 Generating Mode

In generating mode there is a number of factor which determine whether peaking power is required, and if so, what quantity of energy is available and/or provided at each time step. There are four main limiting factors during generating mode:

1. Peaking Power Required, what quantity of peaking power is required.

2. Unit Capability, the capacity of the pump/turbine units. The model considers single-speed and adjustable speed pumps separately.

3. Water Available in the Upper Reservoir. The quantity of the available water in the upper reservoir for turbine operation.

4. Volume Available in Lower Reservoir, volume available in the lower reservoir. At each time step power can only be generated if there is space available in the lower reservoir to received water. At the first time step the reservoir is assumed to be empty.

The model evaluates each limiting factor and selects the minimum value for further analysis. The Peaking Power Required is calculated from Formulas 3.18, 3.19 and 3.20.

$$E_{turbine} = P_{turbine} \times t \tag{3.18}$$

In Formula 3.18:
$E_{turbine}$ is the energy of the turbine.
$P_{turbine}$ power of the turbine and t the time.

$$P_{turbine} = \gamma \times \Delta H \times \eta \times Q \tag{3.19}$$

Solving for Q we get Formula 3.20

$$Q = \frac{P_{turbine}}{\gamma \times \Delta H \times \eta} \tag{3.20}$$

In Formula 3.20:
Q is the Available Excess Energy.
η is the turbine efficiency (usually around 98%).
ΔH is the net head in meters.
$P_{turbine}$ is the power of the turbine in Watts.
γ is the specific weight of water at 4 °C is is 9807 kg/ (m^2/s^2)

Just like in pumping mode, the Unit Capability, is calculated differently in single speed and in adjustable speed units, because they operate at different efficiencies and generally they have different operation. In this model, though, we assume that they operate similarly. The optimal efficiency a facility can operate is between 70 % - 100 %. Based on the operational characteristics of the units the model considers each pump/turbine unit separately. For each unit, the model assumes that the first unit operates when peaking power is between 70% - 100%. Each subsequent unit is then programmed to turn on once each subsequent interval of peaking power required is achieved. Single speed units operate in a range of flows down to 50 percent of the rated discharge. In order to maintain the optimum efficiency, the operation is limited down to 70%. For each unit the Formula 3.20 is used to calculate the flow (Q). Adjustable speed units have a range of power outputs, down to 30 percent of the rated discharge. But in order to maintain the optimal efficiency they operate between 70% -100% of the rated unit capacity. As mentioned, it is assumed to operate in a similar way to single speed, so for each unit the Formula 3.20 is used to calculate the flow (Q).

The Water Available in Upper Reservoir is the next limiting factor that is taken into account. The equations that are used in order to calculate it are the same as in pumping mode (Formulas 3.16 and 3.17). The only difference is that, during the pumping mode, the volume of water available in the upper reservoir increases and, during the generating mode, it decreases.

The elevation of the lower reservoir at the end of the prior time step is taken into account in order to calculate the Volume Available in Lower Reservoir at each time step.The Formulas 3.17, 3.18 and 3.19 are used in order to calculate the flow (Q).

Example Consider a situation where flow available is Q = 162.76 m^3/s, turbine efficiency η = 92$\%$, the net head is ΔH = 442.66 m, the time period = 3600 s, Power is 629 MWh. Using equation from the Formula 3.16, Volume is calculated: V = Q $\times$ t = 162.76 $\times$ 3600 = 585936 m^3.

Using Formula 3.17 $P_{turbine}$ is calculated: $P_{turbine}$ = $\gamma \times Q \times \Delta H \times \eta$ = $9807 \times 162.76 \times 442.66 \times 0.92$ = 650 MW.

$E_{turbine}$ = 650×1 hour = 650 MWh (using Equation 3.18). [21]

Chapter 4

Pumped Storage Prospects

4.1 Pump Storage Prospects

Nowadays, the concern about global warming and the call to decarbonize electricity resulted in an increased interest in PHES. Many existing hydropower power plants were constructed many decades ago and as a result of this, their equipment is outdated and their technology is judged inefficient. Simple by renovating and upgrading existing PHES facilities makes possible the increasing of the capacity of the PHES plants. Replacing outdated pump/turbines impellers and control systems with new technology equipment are some parts of the procedure that needs to be done in order to upgrade old PHES facilities. Capacity of existing PHES facilities is able to be increased by 15 to 20% and efficiency by 5 to 10%. Moreover, conventional hydropower plants could be re-engineered. A lower reservoir could be added and pump-back units as well in order to pump water back to the upper reservoir during peak-off hours and becoming combined grids which can use with intermittent energy from renewable sources such as wind turbines and solar panels.

There are many pump storage facilities around the world, especially in Japan and the US, but in the next years there are many plans about the construction of new projects around the world. China has made a serious turn to hydropower and especially pump storage facilities. Chinese government want to quadruple its pump storage installations and reach total capacities of 100 GW by 2050. Pumped-Storage is very important to China because it can help in the increasing penetration of both intermittent wind and solar. The most significant PHES projects that are going to be constructed are the Jinyun (1800 MW), Wenden (1800 MW) and the Jixi (1800 MW).

On the other side, the US also have an aggressive plan and have many plans for PHES. Almost 23 GW of pumped-storage hydropower installed capacity belong to USA. US government are planning to increase the total installed capacity of the PHES by 35 GW, nationwide, according to the DOE (US Department of Energy). Moreover, it will add hydroelectric capacity to existing non-powered dams after the U.S. House of Representatives approved a pair of bills for the promotion of these projects. In 2018, during the 2018 government funding bill, the DOEs Water Power Technologies Office made a record with 105 billion USD, with 35 million USD going to Hydro-Pumped storage projects/programs. The most significant PHES projects are the Eagle Mountain with 1300 MW and the Gregory County with 1200 MW.

Furthermore, there are plans from many European countries. Many countries announced or even started the construction of larger and smaller pump storage. Switzerland, has made investments and managed to have a total installed capacity of 2500 MW. One project which is under construction is Nant de Drance PHES plant. The project is being developed by Nant de Drance SA, consortium of three companies Alpiq, CFF and FMV, with a capacity of 900MW. The two major countries in Iberian peninsula, Spain and Portugal, have made a serious turn in the construction of PHES facilities. Portugal is planning to construct one of the largest PHES plant which is the Alto Tamega complex, which will add a total of 1200 MW. Spanish utility Iberdola is responsible for the construction of the project. More specific details can be seen below, where the larger pumped storage facilities, that are announced, planned or under construction, can be seen on the tables below (Table 4.1, Table 4.2, Table 4.3).

As we mentioned earlier, the prospects for the usage of pump-storage hydropower is enormous worldwide. On the tables below are presented the most significant hydropower power storage plants/projects which are under construction, planned and announced. For the tracking of that projects we used Pump-Storage Tool. Pump-Storage Tool maps the locations and vital statistics for existing and planned pumped storage projects. It is a tool which is offered for free by the International Hydropower Association (IHA). On the tables below are presented some major prospects and projects of Pumped-Storage Hydropower. [9] [29] [39]

Name of the PHES plant	Installed capacity (MW)	Country
Mount Ataqa	2100	Egypt
Snowy Mountain 2	2000	Australia
Glinsk	1500	Ireland
Gokcekaya	1400	Turkey
Monontsa	1200	Lesotho
Kobong	1200	Lesotho
Gregory County	1200	US
JD Pool	1200	US

Table 4.1: Announced PHES plants worldwide

Name of the PHES plant	Installed capacity (MW)	Country
Mount Ataqa	2400	Egypt
Atorf	1400	Germany
Eagle Mountain	1300	US
Damoling	1200	China
Bac Ai	1200	Vietnam
Siroka Draga	1120	Bosnia and Herzegovina
Lagobianco	1050	Switzerland
Grindulu	1040	Indonesia
Tarnita-Lapustesti	1000	Romania
Turga	1000	India
Parker Knoll	1000	US

Table 4.2: Planned PHES plants worldwide

Name of the PHES plant	Installed capacity (MW)	Country
Jinyun	1800	China
Jinyan	1800	China
Jixi	1800	China
Wendeng	1800	China
Dunhua	1400	China
Luoning	1400	China
Ninghai	1400	China
PingJiang	1400	China
Xiamen	1400	China
Jurong	1350	China
Tianchi	1200	China
Yixian	1200	China
Upper Cisokan	1040	Indonesia
Tehri	1000	India
Nant de Drance	900	Switzerland

Table 4.3: Under Construction PHES plants worldwide

4.2 Raccoon Mountain

4.2.1 Introduction to Raccoon Mountain Power Plant

The Raccoon Mountain Pumped-Storage Plant located on the Tennessee River 6 miles west of Chattanooga, Tennessee. It is an underground pumped-storage plant. Initial plan for the Raccoon Mountain project was based on the use of a favorable site (Raccoon Mountain) located on the Tennessee River (Nickajack Reservoir) about 10.5 km west of the city of Chattanooga. The head of the upper reservoir is around 70m and the total length is 1800m. The construction of the pumped storage started in 1970 and was delayed about two years by unsatisfactory metallurgy in the stay ring of the turbine because the scroll case required redesign. The trial of the first unit was made in 1978 and the last unit was included in the power system in 1979, one year later. For the next two years many intense modifications in the power system were made. In 2012, the plant stopped from working, due to damage in the generators rotors, but continued the operation in 2014. In national level Raccoon Mountain is a great asset to the Tennessee Valley and the US for the production of renewable electricity. In international level Raccoon Mountain pump storage was the first large scale facility that used the reverse pumped theory and was a model for many reverse pumped storage plants helping in the growth of this theory. Raccoon Mountain pumped-storage plant has four reversible units with a capacity of 413 MW (the total capacity of the facility is 1652 MW), at 0.9 power factor (PF) as generators and 540000 horsepower in the pumping direction. The four vertical-shaft Francis type reversible pump/turbines will have a total nameplate capacity of 1530 MW. Moreover each pump/turbine has a rated power output of 525000 hp at 310.896 m net head and a rated discharge at of 109.019 m^3 /s at 304.8 m total head as a pump. The pump/turbine distributor centerline is located about 39.0144 below normal pool level and at elevation 153.924 m. As for the generators and the motors, each rated at 382.5 MW, at 0.9 power factor, 60 Hz as generators and 540000 hp as motors. At a synchronous speed of 300 rpm all the units are operated and the four units are capable of pumping at a rate of approximately 509.703 m^3 /s at minimum normal head and approximately 368.12 m^3 /s at the maximum head. So average discharge when generating at 1530 MW will be about 594.653 m^3 /s. The upper reservoir is capable of storing 44825568.1678 m^3 of usable water between upper pool elevations of 509.6256 m and 466.344 m. As a result of this 33000000 kWh of available stored energy can be produced.

The lower reservoir is situated in the Tennessee River in a favorable site in Nickajack Lake (Nickajack Reservoir). The upper reservoir of area of 2023428.21 m^2, was constructed by placing a dam across the valley on top of the Raccoon Mountain. It takes 28 hours to fill the upper reservoir. The initial project would have a hydraulic head of 313 meter and could generate electricity for 15 hours with a capacity of 1200 MW. After the passage of years and the modifications the generation of electricity lasts for 22 hours and the capacity is 1652MW. The final cost of the construction of the plant was 328000000 dollars or 198$/ kilowatt of the capability. The general plan and section of the site, with its underground power/plant are shown in figure 4.1. [11] [15] [33]

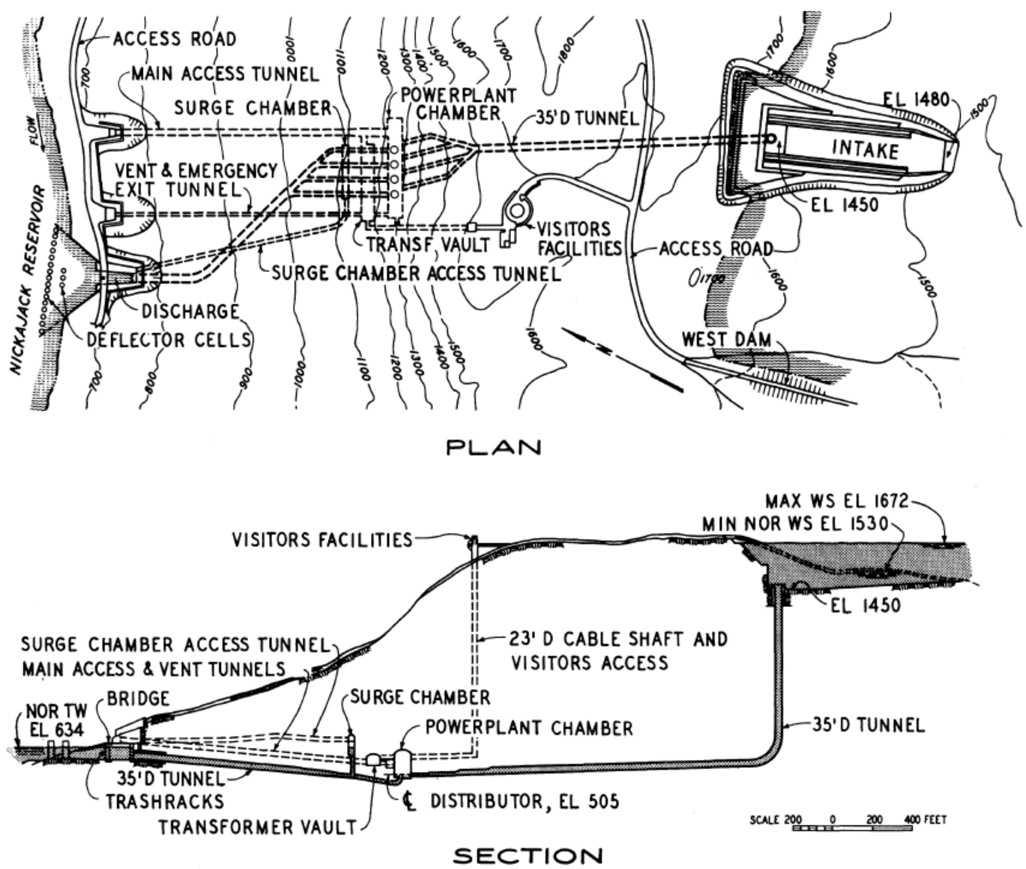

Figure 4.1: Raccoon Mountain Power Plant (Taken from RACCOON MOUNTAIN PUMPED-STORAGE PLANT - TEN YEARS OPERATING EXPERIENCE F. E. Adkins

4.2.2 Operation

The following terms are used in order to describe the steady state condition operation of the units. Shutdown condition where the unit is at rest and disconnected from the rest power system and its associate unit subsystems idle. Moreover the spherical valve and wicket gates are closed in contrast with the draft tube gate, which is open. There is also the emergency shutdown, that is used when there is a function damage. In generation mode unit is synchronously connected to the power system, turning 300 r/min in the counterclockwise direction with draft tube gate open and the spherical valve draft open, the wicket gates throttled open. Meanwhile the pump-turbine passes water from the upper to the lower reservoir. Additionally, there is the Generate Condense Mode. This mode operates in a similar way with the standard generating mode with the difference that the spherical valve and the wicket gates are closed and the tail water is depressed below the run with compressed air. There are, also, three more modes of operation, each of these refers to three of the four motors of the facility. Motor first is consider to be similar to shutdown condition. There is the difference that the tail water is depressed below the pump-turbine runner in preparation for a pump start. Moreover, there is the Motor second operation, in which the unit has a synchronous connection to the power system, turning 300 r/min in the clockwise direction with the spherical valve and the wicket gates closed but the draft tube gate opened and the tail water below the turbine runner. In this mode, the unit operates as a synchronous unloaded motor turning in the direction of the pump.

Finally motor third is synchronously connected to the power system, turning 300 r/min in the clockwise direction with the spherical valve and draft tube gate open. The wicket gates throttled are open and the pump-turbine passes water from the lower reservoir to the upper reservoir. The unit is operating in this mode as a loaded pump. Below we can see the operation changes of the different parts of the unit. [31]

4.3 PHES plants in Greece

Greece is a highland country in percentage of 80%. Thus it consists of rough terrains and many stony grounds. Despite that, it has many lakes and rivers that are eligible for the hydroelectric energy production. Hydroelectric plants are mainly installed in northwestern Greece where the most sierras are located. In modern Greece Hydroelectric development first appeared in 1927 where 4 small hydroelectric plants (Glafkos, Vermio, Agia of Chania, Agios Ioannis Serres) first operated with total power of 6 MW. The rise of hydroelectricity in Greece coincides with the foundation of PPC (Public Power Coorporation).

The pumped storage technology in Greece is implemented in two power plants, one in Thissavros and one in Sfikia. In both of the plants, all units are reversible and are able to act as turbines and as pumps. Pumping and storing of water are activated during the night when there is energy scarcity from the operation of thermoelectric power plants. Pumped-storage facilities can improve the exploitation of the available energy which for the most common hydroelectric power plants is low due to the fact that their operation is limited by the hydrological conditions. During the European project Connecting Europe Facility-Energy Terna Energy has completed the studies and has received production licenses for a project of a total generation capacity of 680 MW in the Municipality of Amfilochia, Prefecture of Aitoloakarnania. Its estimated cost is around 680 euro/KW, annual production around 820

Gwh with total efficiency factor 70%. This project involves three dams, Agios Georgios, Pyrgos and Kastraki. [4] [14]

4.3.1 Sfikia

Sfikia pumped-storage plant is located 20 km away from the city Veria and was completed in 1985. The pumped-storage hydroelectric power station consists of one reservoir. The height of the dam from its founding, is 82m, its length is 220 m and dam volume is 1.62 million m^3. The dam is rockfilled with an inclined core. As for the reservoir, which operates in a daily circle, it can store 99 million m^3 with total reservoir capacity around 18 million m^3. The operation height of the reservoir is 146 m above sea level, the minimum operation height is 141.6 m and the flood height is 147 m. The diverting tunnel has 490 m length, its diameter is 7.5 m and its flow rate is 620 m^3/sec. The spillway capacity of the facility is 1600 m^3/sec. Moreover, there are three power intakes with dimensions 5.6m $\times$ 10.9m and distance between them around 22m. The bottom outlet tunnel is located on the left side of the dam and it is made of concrete. The inner diameter of the tunnel is 3.50 / 3.00 m, the length of the tunnel is 309 m and the maximum flow rate is around 100 m^3/sec. The generating station is in the left side of the dam, is sub-surfaced and consists of three reversible units. For pumping mode there are 3x108MW pumps and for generating mode 3 $\times$ 105 MW. The turbines that are being used are Francis type, with power 143000HP and the facility total voltage is 15750 V. The average fall height is 62 m and operates in 125 rounds/min. In addition for pumping mode the consumption is 0.19 kWh/m and for generating mode 7..2 m^3 /kWh. Finally more specifically the operation date of the Unit I was in August 1985, for the Unit II in September 1986 and for the Unit III 1985. [4] [10]

Figure 4.2: Sfikias pumped-storage plant

4.3.2 Thissavros

Thissavros hydroelectric power station is located in the northern Greece. The Thissavros-Dam is a rockfilled dam with inclined core on the Nestos river, near Drama. PPC is the main owner of the dam. Thisavros is the highest dam in Greece with height of 172 m from the bottom. The dam construction was finished at 1996 and it uses the pumped-storage technology. The total length of the Thissavros dam is 480 m and the volume of the dam is 12 million m^3. As for the reservoir, the reservoir area is 20 km^2 and its capacity is 705 million m^3. Additionally, the area of the catchment is 4258 km^2 and the spillway capacity is 6000 m^3/s.

Thissavros PHES plant contain 3 three identical 120-MVA reversible units equipped with vertical Francis turbines which operate under a net head ranging from 92 to 157 m and units run at 214 r/min. Installed power capacity of the plant is 384 MW (3 $\times$ 128). The powerhouse of the plant is underground with dimensions of 22 m (width) $\times$ 42 m (height) and 100 m (length). After its operational start, there was a damage at the thrust bearing of the units due to excessive axial loading and replaced with new ones employing teflon coating. It is usual for the operation of the plant at night to operate one or more units as pumps which start from another Thissavros unit. The main purpose of Thissavros power plant is for the production of energy in the form of hydropower. In addition other purposes of the plant is irrigation as well as flood control. Finally the mean annual production is around 440 GWh in which are included GWh due to pumping. [4] [18] [32]

Figure 4.3: Thissavros dam.(Taken from YPETHE)

4.3.3 Agios Georgios-Pyrgos-Kastraki project

In Amfilochia, Greece, in Aliakmonas river there is a pump storage project that is under construction and involves three dams the Agios Georgios, the Pyrgos and the Kastraki. This project will be a pump storage complex with two independent upper reservoirs, the Agios Georgios Dam and the Pyrgos Dam, and a common lower reservoir, the Kastraki Dam. The ownership of this project is Terna Energy Group, obtained production license by the Regulatory Authority of Energy (RAE) and the temporary interconnection terms offer, from the Independent Power Transmission Operator (IPTO). The electricity that is going to be produced annually is 816 GWh. The project will work in daily circle, 6 hours for pumping mode and 8 hours for generating mode. In general, the estimated operation for a year is 200 days.

The first upper reservoir, Agios Georgios will have effective storage capacity of 5 × 105 m^3. For generating mode it has 4 reversible units with installed power of 460 MW and for pumping mode it has installed power of 496 MW. The operational height of Agios Georgios is 383 m, while the flood height is 383.65 m and the minimal operational height is 359.5 m. The reservoir storage capacity is 5 million m^3 and the volume of the dam is 620000 m^3. The height of the dam from its founding is 54.5 m and the reservoir area is 318000 m^2.The second upper reservoir at Pyrgos Dam will have effective storage capacity of 2 × 106 m^3. For generating mode it has 2 reversible units with installed power of 220 MW and for pumping mode it has installed power of 234 MW.

The second upper reservoir, Pyrgos will have effective storage capacity of 2× 106 m^3. For generating mode it has 2 reversible units with installed power of 220 MW and for pumping mode it has installed power of 234 MW. The dam height from its founding is 56 m and its volume is 160000 m^3. The operational height is 430 m and the minimum operational height is 412 m. Moreover, The reservoir storage capacity is 2 million m^3 and the reservoir area is 174500 m^2.

The lower reservoir in Kastraki will have an area of around 27.5 km^2 and reservoir storage capacity will be 97 million m^3. The operation height for this reservoir is 144.65 m, compared with the starting which was 142 m and the minimum operation height is 140.65 m. In addition there are common interconnection projects for Agios Georgios and Pyrgos which include 400 kV of Amfilochia and a 400 kV interconnection line with the center of high voltage of Acheloos.

The upper reservoirs of Agios Georgios and Pyrgos are created with the construction of dams by cylindrical hard dump. Each project is made up of some individual constructions which are:

1. The body of the dam with drainage arcade or even tunnel in Pyrgos.
2. Spillway.
3. The baffle duct which is associated with the discharged bottom and the ecological pipeline of supply.
4. The upper water intake.
5. The access roads.

The estimated cost of the project is around 502 million Euros. The main purpose of this project is the maximizing of the penetration of the Renewable Energy Sources in Greece, the reinforcement of the interconnected transmission system and facilitating the exchange of energy between Greece and other EU countries. [12] [14]

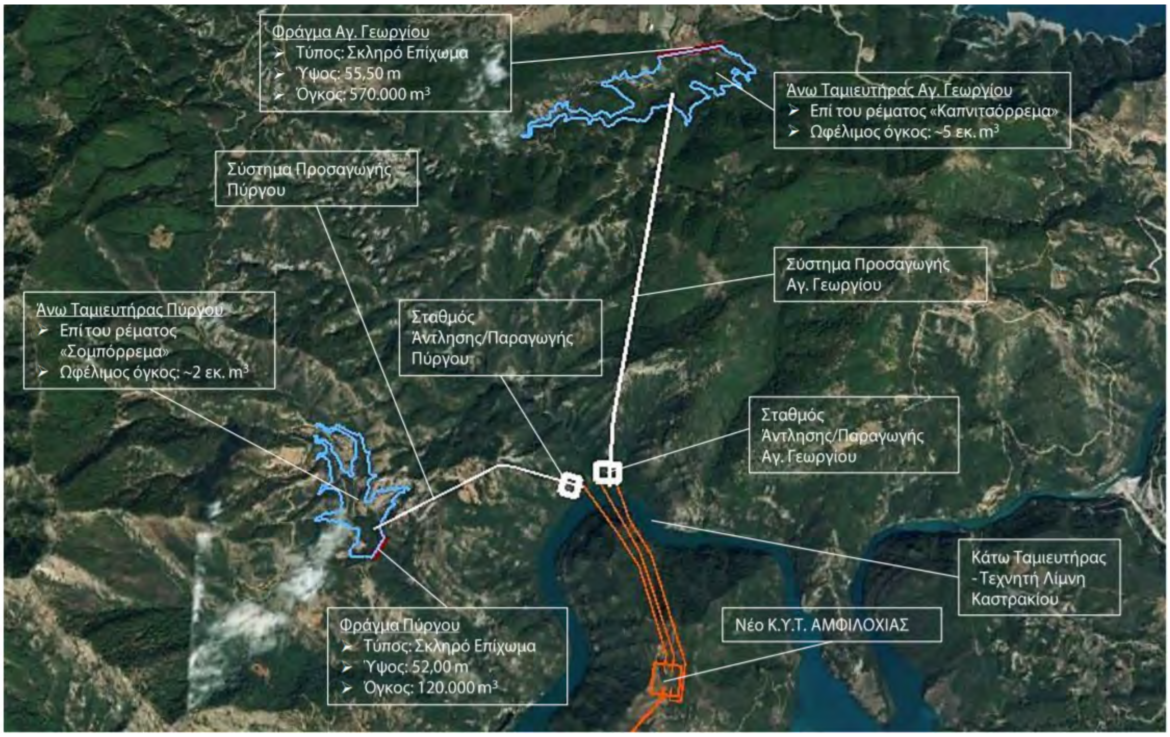

Figure 4.4: Agios Georgios-Pyrgos-Kastraki project locations. (Taken from Terna)

4.4 New Pump Storage Prospect in Greece - A Case Study

As mentioned, Greece has already two operating pump storage facilities, in Thissavros and in Sfikia, and one under construction, in Agios Georgios-Pyrgos-Kastraki. Despite that there is more potential in pump-storage technology in Greece due to the morphology of the country. The great number of rivers and lakes benefit the existence of many dams, so Pump-Storage projects can be favored.

4.4.1 Selection Criteria for the suitable Dams

In this case study we will examine the dams which can favor the construction of Pump-Storage projects. In order to decide the perfect dams for our study, we took into consideration a few major factors. To begin with, the first factor that we considered is the height of the dam from its founding. Then we examined the purpose of the dam, as well as the reservoir capacity of the dam. We considered that a desirable height of the dam, which will satisfy the requirements of the construction of a PHES plant is at least 50 m. In addition, as for the reservoir capacity we assumed that a capacity 3 million cubic meters is favorable. Finally, for the purpose of the dam we focused primary on dams which are used for hydrolelectric production or on dams which use primary for hydroelectric and secondly for other purposes. Thissavros Dam, Sfikia Dam and Kastraki Dam will not be included because they are already in pump-storage projects that operate or are under construction.

In general, in Greece there are around 145 dams. The dams that fill the requirements from our assumption are 11:

- Asomata Dam
- Ilarionas Dam
- Ladonas Dam
- Kremasta Dam
- Messochora Dam
- Piges Aoou Dam
- Platanovrissi Dam
- Polifito Dam
- Pournari Dam
- Sikia Dam
- Tavropos Dam

In the next subsection we will examine the case of Pournari I as upper reservoir and Pournari II as the lower reservoir.

4.4.2 Case Study Pournari I and Pournari II

The case study of a pumped-storage system regards two hydropower plants in Aracthos river in Greece which are Pournari I and Pournari II. We are going to examine the combination of these two as a pumped-storage facility with Pournari I as the upper reservoir and Pournari II as the lower reservoir. Pournari I hydropower plant uses three Francis turbines with a capacity of 300 MW. Pournari II is equiped with two Bulb type turbines of 16 MW and an S-type turbine unit. The data for the two hydropower plants can be seen in the table below.

Location	River	Head(m)	Volume of the Dam ($10^3\ m^3$)	Reservoir Capacity (hm^3/s)
Pournari I	Aracthos	120-100	9000	303
Pournari II	Aracthos	40-33.4	700	4.1

Table 4.4: Data for Pournari I and II

We assume that the facility will operate on a daily cycle and it will pump for 7 hours and generate for 5 hours. The facility will operate in pumping mode during the hours of the day when the energy demand is low (mostly during night) and so is its cost. In contrast, when the energy demand is high and the energy is needed in the grid it will operate in generating mode. The daily operation cycle doesn't benefit the the maximum value of reversibility. Weekly, it will work for 5 days a week and it will operate 35 hours for pumping mode and 25 for generating mode in total. This operation is mostly done for the regulation of the electricity grid. Pournari I will continue to operate as a hydroelectric dam unless the reservoir capacity is full and there is flood danger. We assume that Pournari II is going to have an identical scheme to Pournari I, with same installed power of 300 MW. As a result of this Pournari II power station has to be equipped with three reversible Francis turbine units. Powerhouse of Pournari II is going to be responsible for the control of the grid.

From the data given we can easily calculate the net head that will be used in our research is the difference of the mean head of Pournari I and the mean head of Pournari II. That means the net head is 73.3 m. (((120+100)/2) - ((40+33.4)/2) = 73.3 m).

The efficiency is assumed to be 0.85. The volume of water that will be pumped from Pournari II to Pournari I is 4.1 hm^3 which is the capacity of the reservoir of Pournari II (lower reservoir).

So using the Formula 3.17 from chapter 3 we can easily calculate the flow for 7 hours:

Q_{pump} = $4.1 \times 10^6/(3600 \times 7) = 162.7m^3/s.$

Using the Formula 3.14 we calculate the power of the pump that is needed in order to pump the water from the lower to the upper reservoir.

P_{pump} = $9807 \times 162.7 \times 73.3/0.85 = 137.6MW.$

The energy of the pump is calculated from formula 3.13:

E_{pump} = 137.6 MWh.

As far as concerned the generation mode , we calculate the flow using the Formula 3.17, assuming time of 5 hours. So:

Q_{gen} = $4.1 \times 10^6/(3600 \times 5) = 227.78m^3/s$

Now for generating mode using the Formula 3.19 we get the total generating power, having a total discharge (flow rate) of 228.78 m^3/s :

P_{gen} = $9807 \times 227.78 \times 73.3 \times 0.85 = 139.17 MW$.
The energy of the turbine will be calculated from formula 3.18:
E_{gen} = 139.17 MWh
Annualy, it is estimated to operate for 261 days so it is estimated to produce 36.3 GWh.

It must be made clear, that the maximum volume that facility it can handle is the 4.1 hm^3 of the Pournari II and any addition to this creates flood danger. As a result, the creation of a PHES facility in Pournari I ans Pournari II have many advantages, the greatest being the expansion of the facility with the addition of installed capacity. The operation of the facility as a pumped-storage plant as well, is estimated that is going to add around 36.3 GWh on an annual basis.

This case was done for the Dams Pournari I and Pournari II and shows the advantages of Pumped-Storage technology. Similar studies can be done for the rest dams that we have selected above and the application of Pump-Storage could increase the power generation and could assist the energy demands of Greece.

Cost Analysis

First of all the main characteristic of PHES projects is the long life span. Project costs are depended from the construction site, with costs varying from 400 - 3000 euros per kW. The energy storage and MW capacity at any given site in combination with the installed power determine the capital cost of the PHES project.

The cost of the energy during pumping mode is not expensive, due to the fact that pumping happens during the night hours in periods with low demand. In contrast, during generation mode there is a higher energy demand and the electricity that is produced is sold higher. As a result of this the difference between the pumping and generating power plays an important role for project evaluation. For a pump storage facility to be viable, the price of the energy that is consumed for pumping and the initial costs must be lower than the price from the electricity that is produced. Generally the main costs for one pumped-storage project is the initial costs and the maintenance and operation costs.

In general, maintenance and operational cost are low for a pumped-storage project. These kind of projects have long life cycle. Operational and maintenance cost are depended from a number of factors. First factor is the owner operation philosophy, and the time owner decides to perform maintenance on the equipment of the plant. Secondly, is the age of the project. The elder the project the higher are the costs for the maintenance and the operation. In addition the type, number and size of the pump/turbine units affect directly the maintenance and the operation of the plant. Moreover the way of the operation of the project is important for the costs for example if operation is done through remote control for example. Finally operation and maintenance costs are connected with the characteristics of the reservoirs like the type, size and configuration.

The initial capital costs are difficult to identify due to large variation of the sites, the morphology, and the environmental considerations. In order for the initial costs to be calculated there are a few things that must be taken into account. The first is the permission costs in order to operate the facility. Then is the design and planning costs, which are essential and differ from each PHES facility and each site. In addition, there are many essential costs which include land acquisition, purchase of water rights and public relationships. Finally, the most important cost is the construction cost for the reservoirs and the electrical equipment of the machines that are about to be used in the facility.

As far as concerned our study case Pournari I and Pournari II project, according to Study of pumped storage schemes to support high RES penetration in the electric power system of Greece of Anagnostopoulos and Papantonis, the cost of the project for the purchase, constructions and installation is around 450 euros per KW. So the cost of the construction of power station in Pournari II is around 62 million euros. According to the Independent Power Transmission Operator (IPTO or ADMIE) the electricity is bought from the PHES facility for 87.85 euros per MWh. So in our case the price that we get for 1 year is 2.94 million euros. According to our calculations the cost that is for operation during pumping mode is around 1.3 million euros. So in a year there is a profit of 1.64 million euros. On calculation above we didnt take into consideration the maintenance costs. Moreover, the Pournari II is already constructed so the initial cost may be lower. [17] [21] [29]

Chapter 5

Conclusion

In the modern world with growing awareness among people, clean energy sources are recommended for global use. As the energy demands and the environmental issues, like global warming, expand day by day the humanity and the planet must find solutions to these problems. One solution that can help is the energy coming from the renewable energy sources. This energy can not only help the planet but can confront huge energy problems like the fossil fuels depletion. Renewable energy sources are essential for the humanity nowadays.

A renewable energy source that is a great asset, is the hydropower, the energy that comes from the mechanical movement of the water. Hydropower technologies are quite mature, with many years of history and can provide many quantities of carbonless energy. There are many ways to generate hydroelectric power with the advance of the turbine technology. Nowadays it can be made quite clear that every country are investing in this kind of energy production with China and USA as the pioneers of this cause.

Energy storage technologies plays a very important role to the penetration of the RES (Renewable Energy Sources). Pumped-Storage technology is one of the most important and promising technology between energy storage technologies with great efficiency. Pumped storage hydropower is considered to be a proven a great scale energy storage technology as it permits storage of excess energy for later use. Moreover, it helps to the integration of renewable energy in to the power grid.

In this thesis the design characteristics, the operation and in general the model of Pumped-Storage technology were analyzed. In addition, Pumped-Storage projects, plans and prospects all over the world were examined. A country with great morphology (many lakes and rivers in combination with highlands) that favors the hydroelectricity generation is Greece. The two main Pumped-Storage plants in Greece, in Sfikia and Thissavros, were presented along with an under construction future plant, the complex in Agios Georgios-Pyrgos-Kastraki. Furthermore, a case study in Pournari I and Pournari II was developed based on a model for the evaluation of the concept of developing pumped storage schemes in existing hydroelectric plants. The results of this model showed the potential of the application of Pumped-Storage technology on the existing hydropower plants of Pournari I and Pournari II. Numerical analysis proved that pump-storage application could help on the production of energy, with quite efficient operating strategy in respect of the most cost-effective pumping power unit.

From this thesis, consequently, it is clear that pumped storage needs of the electric system should be distributed to several hydroelectric sites. Moreover, it can assist many existing hydropower plants and expand their total installed capacity. Finally it is a promising technology and will play a major role with great investments in the future in parallel with the development of RES production.

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