Life Cycle Assessment of electricity generation from hydropower

Aristeidis Karananos

SID: 3303170004

SCHOOL OF SCIENCE & TECHNOLOGY
A thesis submitted for the degree of
Master of Science (MSc) in Energy Management

DECEMBER 2018
THESSALONIKI – GREECE
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Abstract

This dissertation was written as a part of the MSc in Energy Management at the International Hellenic University.

In the current dissertation a study is made, where the impact of the construction and operation of a hydropower plant is assessed. To produce the impact assessment results in question the software openLCA is used. The power plant used in this paper is considered to be located in Greece and of the storage variety with a concrete dam and an installed capacity of 100MW for electricity production. The categories selected are global warming potential, acidification and eutrophication, all expressed in kg of their equivalent per kWh of electricity produced. In order to interpret the results, they are compared with two other electricity production methods, mainly a lignite power plant and a plant that operates with natural gas. In the end, the results show that the environmental impact of a hydroelectric power plant in Greece is considerably smaller compared to fossil fuels operated installations. The main reason is the use of a free fuel which is water. The biggest impact of a hydroelectric power plant is considered to be the land transformation because of the construction of the dam.

Aristidis Karananos
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A big thank you at both organizations in Greece and Germany, most importantly the DAAD for funding this project and for their great collaboration and for giving me the chance to travel to Germany in order to complete my dissertation.

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Thessaloniki, December 2018
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1 Introduction

Global demand for energy is constantly increasing. According to estimates of the International Energy Agency (IEA), the needs of the planet will increase by 35-40% over the next 15 years, mainly due to its significant increase of the population of the earth, the growth of economic and developmental activities across the globe and a significant improvement in living standards level and what this entails. [1]

The reserves of the planet's fossil fuels (coal and oil) are not renewable and will be exhausted within a foreseeable period. Furthermore, the consumption of fossil fuels has caused and continues to cause significant damaging effects on the environment, such as greenhouse and acidic rainfall, as well as major climatic changes, which are large threats to the future of humanity. From measurements made, emissions of carbon dioxide (CO2) in the atmosphere are steadily increasing year by year with the Electricity Production sector being the largest direct participation in these emissions. [2]

It is, therefore, imperative to reduce our dependence on the conventional forms of energy and replace them with others, renewable and friendly to the environment. Studies show that the total potential of Renewable Energy Sources (RES) is at least 20 times larger than what is used today. [3]

Solar energy, wind energy, geothermal energy, hydropower, biomass or even urban waste are forms of renewable energy sources of energy, the exploitation of which has, in addition to economic benefits, positive environmental and social impacts on sustainable development with ecological perspective.

More specifically, as far as hydroelectric energy is concerned, environmental benefits of a hydroelectric plant are varied. Even the downside of their environmental impacts due to large-scale civil engineer projects, which a large hydroelectric project requires with one well-designed study, can be turned into an advantage. Typical is the case of the Nestos complex in Greece, where after flooding the area in order to create the Dam, a new wetland was created, which soon turned into an important tourist attraction while giving new irrigation possibilities to the surrounding area.

In this study we are going to compare different ways of producing electricity and examine the results. The focus will be the assessment of the global warming potential of each method, as well as the cumulative energy demand. Some types of electricity generation outside of hydro power will be lignite and natural gas, since these are the main
uses of power production in Greece. The method used to create this analysis will be a Life Cycle Assessment from cradle to grave of the power plant. Cradle to grave includes the production from the beginning, taking into consideration raw materials, transport, usage and decommission–recycling. We will also check the acidification as well as eutrophication results of each method of electricity production and compare.

This study is based on input data collected from previous papers and research concluded all over Europe. The main source is the paper titled “Life Cycle Inventories of Hydroelectric Power Generation” by Karin Flury, Rolf Frischknecht, commissioned by Öko-Institute e.V. [9] With this data a reference hydro power plant is created with an approximate installed capacity of around 100MW with a reservoir and electricity net annual production of around 200GWh/a. The reference plant is very similar to the HPP of Platanovrisi, located at the Nestos Complex in Northern-Eastern Greece.
2 Energy Sources

By 2020 almost a fifth of all energy consumption in the European Union must come from renewable sources. This means hydro, solar, wind, biomass and wave energy. This proposal was signed in 2007 by all EU leaders and was created in order to try and cut down on greenhouse gas emissions by 20 percent compared to 1990 levels. [4]

For hydroelectric power, this mandate means significant growth in development and creation of new capacity and important updates to existing facilities throughout Europe. There have been many new plants going into operation in the last years which has not been the case for hydro power for quite a while.

Small hydro power plants (<10MW) have seen more significant development opportunities. This happens since the cost of creating and operating a small Unit is much easier than creating new hydro power plants from scratch. The licensing as well finding the appropriate place for the installation is much easier and can be done in a smaller time frame. The European Small Hydropower Association (ESHA) estimates that installed small hydro capacity could reach 16 GW of installed capacity by 2020.

Europe is a major player and leader in research and development of new technologies. The commitment to R&D as well as to commercialization of new designs continues throughout Europe.

2.1 Renewable energy sources

The increase of population as well as the improvement of living standards have led to a rapid increase in energy consumption with the highest upward trend being observed in the developing countries like China and India. The international research community and the energy industry have turned their interest into modern “clean” production technologies and the use of Renewable energy sources. (RES).

RES is the most environmentally clean energy generation technology available and appears to have drastically reduced the constantly increasing environmental problems. Even though many steps have been taken and new technologies have been developed, the implementation of RES is still at an early stage. Exploitation of sun, wind, water, geothermal and biomass, sources that are environmentally friendly can be made economically viable to contribute to the sustainable development.
In Greece there is the possibility of significant utilization of renewable sources, like solar heating and electricity production from PVs since there is significant sunshine and right wind potential especially on the islands. Water potential is also an option in mountain areas.

In the Figure 2.1 below a graph is created from available data from the European Union. It shows the progress of renewable energy production by type for a time period of 10 years. All results are expressed in tons of oil equivalent (toe). In such cases toe is the amount of energy released by burning one tone of crude oil. Using this unit helps with the comparison between different energy types. As the figure shows, electricity from hydropower has been steady for many years now. This is mainly because old hydro power plants are still in use and having long expected lifetime (explained in the next chapters) new ones are not in major need. On the other hand, renewable energy like solar electricity production has been on the rise. Wind power also has seen a major increase.

Figure 2.1: Renewable production in Europe, source www.datamarket.com [5]

2.2 Electricity from Hydropower

The hydropower that is installed in Europe totals approximately 179,000MW. Countries that have one of the biggest amounts of installed hydro are France, Spain, Italy and Norway. The big goal for European countries is to maintain but also upgrade the existing infrastructure. Retrofitting hydro power plants with more modern equipment,
which mainly means upgrading the capacity is of high priority. Eastern Europe is following a slightly different path, mostly trying to rehabilitate aging plants that have been left unused for quite some time. [6]

In the Figure 2.2 below we can see the production of energy via hydro power in Europe. The color indicates the intensity of the production.

![Figure 2.2: Hydro power production in Europe, source www.datamarket.com][5]

### 2.3 Energy situation in Greece

The Greek energy sector is still mainly dependent on fossil fuels. In the case of natural gas, it is mainly imported, lignite on the other hand is produced at site. Because of the geographical position of Greece and the many islands, about 54% of the energy requirements are covered by petroleum products which is much higher than the average of Europe, which stands at 33%. Islands have been known to produce their electricity from inefficient diesel generators. There have been moves to connect the islands to the mainland, but it is a process that demands many resources and planning.

The Figure 2.3 shows the electricity mix in Greece as it stands for the year 2016. Installed capacity of the hydro power plants in Greece has a total of 3061,1 MW. All this information is provided by the Public Power Corporation of Greece.
The energy sources in the mainland include lignite for around 50% but also renewables like hydro power plants, solar, wind and biomass. Greece imports most of its energy, and primary needs are covered at about 60% from imports. The rest 40% is covered through own production of electricity. The split between lignite and renewables sits at a 60-40 at the moment. Imported natural gas has been slowly picking up as one of the main ways to also produce electricity, which in turn mitigates the need and use of lignite power plants. In the last few years there have been some decommissions of old lignite plants. Those have been replaced either with natural gas plants or with more renewable methods.

According to the Electricity Market Operator (ΛΑΓΗΕ) the total installed capacity in Greece at the end of 2016 was 16,615MW. From this amount 3.912MW were available from lignite power plants, 4.658MW from natural gas, 3.173MW from large hydro-power plants and 4.873MW from renewable sources. The total electricity generation in Greece for the year 2016 was measured at 41.6 TWh. For this production lignite played produced 25%, natural gas 28% and hydro power around 20%. The rest 27% was again covered via wind, solar, biomass and small hydro.

According to the literature, the electricity consumption in the reference year of 2016 in Greece was 50.1 TWh. This amount also includes transmission and distribution losses of around 3%. The annual peak load for mainland Greece was measured at 9.082 MW.
Cost wise, the production of RES has costed less in the year 2016 in comparison to another reference year of 2014. The production of 1 MWh from renewables fell to 160€/MWh which is almost 40€ less from the year 2014 (200€/MWh). This has happened because of the new more efficient technologies used for electricity production but also because of the Feed-in-tariffs (FIT) that the Greek government implemented.

Figure 2.4 consists of data available for Greece between the years 2005 to 2016. It shows the development and emerge of renewable production in Greece. Hydro power plants have been steady, similar to figure 2.1 where European installation was shown. The main increase is happening at solar photovoltaic installations in Greece in the last 4 to 5 years. This was due to government programs helping with new installations and offering contracts like feed-in-tariffs and subsidies. This has stopped in the years of the Greek crisis but is going to continue growing as the financial situation becomes better.

![Primary production of renewable energy by type](source)

**Figure 2.4**: Renewable production in Greece, source [www.datamarket.com](http://www.datamarket.com) [5]

### 2.4 Hydropower in Greece, a look back

Electricity production in Greece started at around the year 1900 in the capital, Athens. Some years later, big corporations from around the world started emerging as possible candidates for electricity production and distribution. The American company Thomson-Houston with the participation of the National Bank would establish the
Hellenic Electricity Company that would be responsible for bringing electricity to the rest of the Country.

The first Greek hydroelectric plant was the Glafkos factory, which is based in the southern part of Greece. The first dams that were constructed were Louros in 1954, Ladon in 1955 and Tayropos in 1959. All three of them were made from concrete and used different styles. (arc dam or gravity dam etc.). Following another dam, the Kastraki Dam, Greek efforts focused on the studies and construction of dirt and stone dams. Thus, such dams were constructed in Polyfyto in 1974, Pournari in 1981, Sfikia and Asomaton in 1985, Stratou in 1989, Aoos Springs in 1989. At the end of 1997 the construction of the dams was completed.

Dams created by the Public Power Corporation (PPC), although they have high manufacturing costs justify their existence because the production of hydroelectric power mitigates the cost of construction as evidenced by the history of the first dams in Greek space. In addition, PPC dams help with irrigation and water supply.

2.4.1 Hydro power plants operating in Greece

The total installed capacity of PPC's Hydroelectric Stations is 3,060MW. (16 large and 8 small stations). The total average annual energy output is approximately 5000Gwh. Hydroelectric Stations today are separated in four (4) main Complexes, two independent HPP and other small ones.

1. Acheloos Complex: (Kremasta, Kastraki, Stratos I and II, Giona and Glafkos). Total installed capacity 925.6MW.
2. Aliakmonas complex: (Polyfyto, Sfikia, Asomatos, Makrohori, Agras, Edessaios, Vermie). Total installed capacity 879.3MW.
3. Arachthos Complex: (Aoos Sources, Pournari I, Pournari II, Louros). Total installed capacity of 553.9MW.
4. Nestos Complex: (Thesaurus, Platanovrisi). Total installed capacity 500MW.
5. N. Plastiras installed capacity 129.9MW.
6. Ladonas installed capacity 70MW.
7. Other small HEIs (Agios Ioannis Serres, Agia, Almyros). Total installed power 1.3MW.

Hydroelectric power today of 3,060 MW (data 2015) covers 28% of the total of installed capacity of the conventional stations which amount to 11.079MW. The average
annual hydroelectricity production, depending on the amount of water available for the year, covers around 9-10% of PPC's production. [7]

2.5 Other possible roles of hydro power plants

Hydro power plants are mainly used for electricity production but in fact they can play other important roles. Sometimes dams for example are built in order to help with irrigation purposes of an area and then a HPP uses the existing construction for the benefit of producing electricity.

Agriculture is affected mainly from seasonal weather changes. Such risk can be reduced by using the water in a reservoir for irrigation in order to maintain stable levels of water usage.

In other cases, dams are created in order to help with flood control. That is their main purpose in places where the level of a river for example is not stable and can cause problem with the population living beyond the point of the dam.
3 Hydro power plants

Hydro power plants convert the energy of the waterflow into electricity. Hydroelectric units exploit the natural process of the water cycle. More specifically because of heating and winds on the surface of the Earth, the water evaporates and gathers on the sky creating clouds. The water vapor is condensed, liquified and then while falling as rain, it enriches the water repositories of the earth, where it returns to the sea, lakes or just underground.

The capacity of electricity generation depends on many factors, such as:

- The flow of water
- The volume of water
- The level of the head created by the dam
- The efficiency of the power plant technology

3.1 Defining hydro power plant terms

A dam is a structure made out of concrete or locally available material. It is constructed in the water flow to block its way in order to gather water.
• The **reservoir** is the artificial lake or water buffer created by the dam.
• The **head** is the elevation difference between the upstream and downstream water.
• The headwater is lead through the **intake** to access the penstock after passing the gate. The gate is closed if the power generation needs to be halted.
• High pressure steel **penstock** pipes deliver the incoming headwater to the turbine. In case of low head power plants penstocks are substituted by open waterways.
• A **turbine** is a rotor in a housing that converts energy from the water flow into useful work and delivers it to the generator through the rotation of its shaft.
• The **generator** utilizes the useful rotational work of the turbine to convert it into electricity

### 3.2 Types of hydroelectric power plants

#### 3.2.1 Run-of-river plants

![Run-of-river HPP](source: KPMG, Central and Eastern European Hydro Power Outlook [8])

Figure 3.2: Run of river HPP

Most common type between other hydroelectric powerplants. They use the natural flow and elevation drop of a river to generate electrical power. This means there is only minimal or no storage of water. Such power plants (PP) are constructed on rivers with a steady and consistent flow. In case of seasonal fluctuations large reservoirs are needed in order to operate the PP during the dry season.

#### 3.2.2 Storage hydroelectric power plants
The distinction between storage PP and run-of-river PP can be made by the purpose of the dam. Run-of-river plants need the dam to create the appropriate head and tailwater level difference for the operation of the turbine, the storage type PP need the dams to store the appropriate amount of water on rivers, where we cannot ensure stable, continuous operation. The reservoir allows for a scheduled use of the stored potential energy of water, flowing from a high to a low place.

The way the system works is that the reservoir is filled when there is rainy season and the summoned water can last for the whole season. The water flows from the reservoir via pressure pipes to drive the turbine of the PP.

![Diagram of a storage HPP](source: KPMG, Central and Eastern European Hydro Power Outlook [8])

**Figure 3.3: Storage HPP**

### 3.2.3 Pumped storage power plants

Pumped storage power plants (PSPP) are known as power plants but are in fact electricity storage facilities. They are a special type of storage plant since the water is pumped up from a lower basin to fill the reservoir. The pumping normally takes place at night, since at that time of day there is excess electrical power (off-peak demand) which is used to dry the pumps. The plant is a net consumer of energy overall with a pumping efficiency of 75-80%.

The main purpose of such plants is balancing the electricity demand and also satisfying peak demands and also utilizing electricity surplus on the side. Since energy cannot be destroyed, it is simply put to use otherwise.
3.2.4 Small hydropower stations <1MW

In the last years many more small hydropower stations have been evolved and created in order to provide more electricity at a lower cost. Mainly the small HPPs have the ability to be far cheaper and also cover a lot less space. This in conclusion means that the effect that such stations have in their surroundings is less evasive. An average size of small HPPs in Europe is around 1.2MW installed capacity, able to produce around 7GWh per year. They are mostly situated in ravines and rivers but also in other infrastructures like waste water treatment facilities or tunnels.

3.2.5 Other forms of electricity production from hydro

There are two other ways of electricity production using water, the ones that use tidal and wave energy. They are connected to sea water movements. These plants are currently in pilot phase and cannot be used as an example in a comparison.

3.3 Turbine types and application

3.3.1 Reaction turbines
The runners of the reaction turbines are placed under water and use the speed of water (its kinetic energy) and pressure difference. They are used mainly at low (<30 meters) and medium head operations (30-300 meters)

Most common types of reaction turbines are:

Table 3.1: Reaction Turbines

Francis turbine

- Most common water turbine technology
- 90% efficiency
- Medium altitude
- Medium water flow

Figure 3.5: Francis Turbine

Kaplan turbine

- Modification of Francis
- Regulate flow/blades
- High efficiency level
- Smaller altitude head operations
- Significant water flow

Figure 3.6: Kaplan Turbine
3.3.2 Impulse (action) turbines

Impulse turbines use the kinetic energy of free-falling water jet that is moved through a nozzle to drive the turbine. They are not submerged into water like the reaction turbines and do not use the difference of water pressure to work.

Table 3.2: Impulse Turbines

Pelton turbine

- Water jet from high altitude
- 92% efficiency
- Very high altitude
- Light water flow

Table 3.3: Turbine Type and Head Classification

<table>
<thead>
<tr>
<th>Head Classification</th>
<th>Turbine Type</th>
<th>Turbine Type</th>
<th>Turbine Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Impulse</td>
<td>Reaction</td>
<td>Gravity</td>
</tr>
<tr>
<td>High (&gt;50)</td>
<td>Pelton</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turgo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium (10-50m)</td>
<td>Crossflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turgo</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi-jet</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pelton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low (&lt;10m)</td>
<td>Crossflow</td>
<td>Propeller</td>
<td>Overshot waterwheel</td>
</tr>
<tr>
<td></td>
<td>Undershoot</td>
<td>Kaplan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waterwheel</td>
<td>Francis</td>
<td>Archimedes screw</td>
</tr>
</tbody>
</table>

Source: http://greenbugenergy.com/get-educated-knowledge/types-of-turbines
Source: http://greenbugenergy.com/get-educated-knowledge/types-of-turbines

Figure 3.8: Flow per type of Turbine


Figure 3.9: Turbine Operation
3.4 Expected life and decommission

In order to produce the results needed in this study we must also take into consideration the useful life of such a project and also what happens after the decommission stage and recycling of some if not all materials used in the initial construction.

The actual lifespan of a hydro power plant is shown in the following Table 3.4. In this table the period in which such a construction would be technically usable is shown as a lower and upper limit in years.

<table>
<thead>
<tr>
<th>Station/function unit</th>
<th>Technical lifespan</th>
<th>Aspects to be considered</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Construction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dams, tubes, tunnels, caverns, reservoirs, artificial lakes, surge chambers</td>
<td>80-150</td>
<td>Duration of water rights, quality, decay, security, losses.</td>
</tr>
<tr>
<td>Buildings</td>
<td>50-80</td>
<td>General conditions, wear, quality, state of the art, security, corrosion, maintenance.</td>
</tr>
<tr>
<td>Water catchment, weir, pressure pipes, streets, bridges</td>
<td>40-60</td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical Parts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kaplan turbine</td>
<td>30-60</td>
<td>Security, losses, cavitation, erosion, corrosion, fatigue, reduction in efficiency, state of the art, quality, wear, load, construction</td>
</tr>
<tr>
<td>Pelton turbine</td>
<td>40-70</td>
<td></td>
</tr>
<tr>
<td>Pump turbine</td>
<td>25-40</td>
<td></td>
</tr>
<tr>
<td>Storage turbine</td>
<td>25-40</td>
<td></td>
</tr>
<tr>
<td>Valves</td>
<td>25-50</td>
<td></td>
</tr>
<tr>
<td>Cranes, other mechanical parts</td>
<td>25-50</td>
<td></td>
</tr>
<tr>
<td><strong>Electrical Parts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generators</td>
<td>30-60</td>
<td>Condition of the parts, cleanness, wear, security, quality, maintenance</td>
</tr>
<tr>
<td>Transformers, high voltage facilities, other electrical facilities, monitoring system</td>
<td>30-40</td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>15-30</td>
<td></td>
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</tbody>
</table>

There are many factors that could affect mainly the technical lifespan of a big undertaking such a hydro power plant, and that’s why there are differentiations between storage power stations and run-of-river ones. Also, the speed a turbine turns and operates
plays a big factor in the lifespan of the materials. It is common that turbines with lower RPM have a longer life than those operating faster. [10]

There isn’t that much of a long-term experience regarding hydropower stations and what happens after they have been decommissioned, since the old ones that are already built and are in usage have a smaller footprint and the big ones, like those in China which are only as much as 20-30 years old. This means that there isn’t also much data available about recycling and also disposal of a decommissioned power plant of such size.

Despite all this, it is assumed that the big constructions of such hydro power plants, like the concrete dams and infrastructure will be abandoned at site and not deconstructed. Also, we have to assume, that old and decommissioned power plants are supposed to be replaced with newer ones after their life expectancy reaches the end. Old parts have to be deconstructed in order to give place to new ones. The concrete dams although, are just maintained throughout their lifetime.

In the specific study in this paper and according to the available data, it is to be assumed that hydro power plants are used and then replaced. This is assumed to be happening for all different kinds of HPP, such as reservoir, run of river and small plants.

Table 3.5 shows the resulting values that have been assumed in the current calculation. They are produced from the values in Table 3.4 after being summarized and averaged. The values are expressed in years.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Storage power station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>150</td>
</tr>
<tr>
<td>Reinforcing steel</td>
<td>150</td>
</tr>
<tr>
<td>Steel (rest)</td>
<td>80</td>
</tr>
<tr>
<td>Copper</td>
<td>150</td>
</tr>
<tr>
<td>Explosives (tovex)</td>
<td>250</td>
</tr>
<tr>
<td>Transport</td>
<td>150</td>
</tr>
<tr>
<td>Construction energy</td>
<td>150</td>
</tr>
</tbody>
</table>

4 Life Cycle Assessment

Life cycle assessment is the factual analysis of a product’s entire life cycle in terms of sustainability. With LCA, we can evaluate the environmental impacts of the product or service that we study from cradle to grave. From resource extraction and processing, through construction, manufacturing and retail, distribution and use, repair and maintenance, disposal and decommissioning as well as reuse and recycling. LCA uses the idea of a standardized methodology, which helps make it reliable and transparent. The standards are provided by the International Organization of Standardization (ISO) in ISO 14040 and ISO 14044 which also describe the following stages of an LCA.

When conducting an LCA, a product system is created on which aspects of environmental use and resources are examined, mainly from the beginning (cradle) to the end of the systems lifetime (grave). Three main aspects of a LCA are the following:

1. The whole system that has to be able to create, use and then dispose during the system analysis.
2. The LCA does not study just one phase or an isolated operation, but the whole cycle of a products supply chain.
3. The study gives out results about all environmental and health impacts and does not focus on only one factor.

An LCA study can answer some very central questions. The impact a product system has on the environment, which processes are the ones that evoke those environmental impacts and also if there is an option for a product improvement towards better efficiency and environmental goals.

4.1 Goal & Scope

The goal and scope definition ensure that the LCA is performed consistently. The LCA models a service, product or system life cycle. Using the LCA we are actually using a simplification of a complex reality and this means that some results might be distorted in some way. The challenge of the person doing the LCA is to develop the model in such way that the simplifications or things that are taken into account don’t influence the results too much. In order to achieve something like that the goal and scope of the LCA study must be carefully defined.
In the goal and scope the most important (often subjective) choices are described, such as the reason for executing the LCA, a precise definition of the product and its life cycle, and a description of the system boundaries.

In this paper our goal and scope are to estimate the impacts of electricity production/generation from a reference hydro power plant. In order to do that, a power plant has to be modeled for the country of Greece and using data from literature and primary data from the HPP site, results are obtained. A purpose of such a study is to gain some insight of environmental impacts from such a way of power generation.

Some target audiences of such a study are parties with interest in environmental impacts, such as government or potential clients and business associates. In cases where renewable energy is used, as in this case, the results may also be used to compare different methods of electricity production in order to achieve a conclusion on order to choose a preferable method.

4.2 Inventory analysis

In the inventory analysis, we look at all the environmental inputs and outputs associated with a product or service, such as the use of raw materials and energy, the emission of pollutants and the waste streams. This is where we get the whole picture of what we are about to study.

For the data collection procedure, specific data is collected at the construction site and also from other similar installations. Some data, like production and transport of materials can be taken from a database like the Ecoinvent database used here.

4.3 Impact assessment

In the life cycle impact assessment (LCIA), we are able to draw the conclusions that allow us to make better business decisions. We can classify the environmental impacts, evaluate them by what is most important to the company that asked for the LCA, and translate them into environmental themes such as global warming or human health.

The most important choice to be made is the desired level of integration of the results. This usually depends on how we would like to address the audience and the ability of the audience to understand detailed results.
4.4 Interpretation

During the interpretation phase, we check that the conclusions are well-substantiated. The ISO 14040-14044 standard describe a number of checks to test whether conclusions are adequately supported by the data and by the procedures used. This way, we can share the obtained results and improvement decisions with the world without any surprises.

4.5 Input data

In order to run the LCA we have to create a reference hydro power plant. The one we are going to use as a model is the HPP from the North East Complex, Platanovrisi. This HPP has an installed capacity of 115MW which is an average size for a Country like Greece. This also gives us the opportunity and ability to compare the results with other electricity power plants using alternative fuels, like coal or even renewable sources.

The data used in order to conduct this LCA come from two categories. The first one has data from the foreground, which includes efficiencies, technologies, installed capacity, emissions etc. that have been obtained from technical reports, papers and literature. They combine data from mainland Switzerland and also some modifications for the non-alpine regions of Europe. The data does not show much differentiation between Switzerland and Greece. This helps in order to keep the error as low as possible while using data from another region. The background data have to do with raw material extraction and acquisition, the transport of equipment and fuel needed as well as the construction and decommission of the plant. Most of these are included in the Ecoinvent database used with the openLCA software.

Figure 4.1: Visualization of an LCA study
4.6 Functional unit

In order to get a correct interpretation of our data we have to create the reference plant in such way, that we can compare our results with other studies. It is known that the size of a reservoir and the electricity production from a specific sized turbine does not produce linear results in the impact categories in study here. [11] This is why a functional unit of “1 power plant” would mean nothing to the comparison between different sized hydro power plants, as well as other electricity producing plants like lignite and natural gas. This is why data for different hydro power plants around the European region are gathered and then averaged in order to produce 1 reference power plant.

After that, the emissions are measured per 1kWh of electricity produced. This is also the way to use other different studies and papers from other power plants as mentioned before to find the main reasons for the emissions produced during the life cycle of a power plant.

4.7 System boundaries

In order to create a Life Cycle Assessment of a specific item, one must set the system boundaries. This process shows us which processes in the products life cycle are included in the LCA. In the Figure 4.2 the whole process shown, which consists of the system boundaries of the study. Outside of these walls the effects are irrelevant. Everything begins with the production of the raw materials, which then become the main construction which is transported to the location site. After that the equipment is built together with the power plant. In the end the output is kWh, which is then compared with the emissions in question.

In the System Boundaries all core processes must be included. This means the energy conversion process of the selected plant, including the need of operation and maintenance, meaning oil, hydraulic liquids for the correct use of the machinery but also possible emissions to the waterways. Electricity must also be taken into account during the production but also operation phase.
In the following Figure 4.4 the system boundaries of 3 different types of power plants are presented and also compared. In the case of both coal and natural gas power plants there is a significant amount of work needed in order to get the supply of the raw materials.
In the case of coal power plant there is mining included in the system boundaries, whereas in the natural gas power plant there is extraction. Both of these activities play a major factor in the end results and affect the energy consumption and emissions. In the case of the hydro plant, there is no fuel needed in order to run the plant, which means that after the construction phase the operating costs, outside of maintenance, are miniscule compared to those of traditional plants.

Figure 4.3: System Boundaries of different power plants
Hydroelectric Complex of River Nestos North East part of Greece

Figure 4.4: Map of Greece with HPP location
Source: The Hydroelectric production of PPC [7]

Figure 4.5: HPP Platanovrisi and Characteristics
Source: The Hydroelectric production of PPC [7]
The characteristics of the reference plan in Platanovrisi Greece are the following.[7] It has a concrete dam with a height of 95 meters. It has been in operation since 1999 and is mainly used for electricity production and irrigation. The dam can hold up to 57 million cubic meters of water and can produce up to 240 GWh of electricity per year. The turbines are of the Francis variety. There are two turbines operational, both of 58MW capacity each.

4.8 LCA data quality limitations

When preparing an LCA, the most important and demanding part of the study is the collection of the input data. There are different options in data collection. Primary data collected at the site and secondary data which are obtained from libraries and previous studies. In the specific study of the reservoir non-alpine hydro power plant there is some uncertainty because the data was limited and also referred to Europe and not specifically Greece. Actions were taken in order to obtain the original data according to the site location, as well as the specific turbines used in the power plant but was not successful.

Because of the limited primary data available, the Ecoinvent 3 database was used which provided data as good as possible. The technologies used in Greece and in Europe are very comparable. The production losses and the efficiency factors also were comparable. Where data was not available at all, approximations where used from other similar types of power plants. Generally, the data that was used was good and not too much dated. They are good enough in order to be used for such a study obtained here.

Finally, there is also one more hurdle to cross and this has to do with the main purpose of LCA itself and it being used as an environmental evaluation tool. An LCI process is not expected to compare and cover all the environmental impacts of electricity produced from hydropower. The LCA is mainly used to explain environmental burdens in terms of energy and materials used.

4.9 Electricity from fossil fuels

In this paper the results will be compared to those from electricity produced from two other different ways. Both those ways will be fossil fuels. The first being natural gas and the second lignite. They are both very common types of fossil fuels still used
worldwide for the production of steam in order to turn turbines that in turn are connected to a generator which produces electricity.

There are a lot of data available for each lignite and hard coal power plants around the world. Greece has been using lignite, because it is easily accessible. In the past the main electricity production came directly from lignite power plants. The plants that run on lignite were also constructed next to the place where lignite was excavated in order to keep costs low and help increase the value of it. In other cases, such as Germany where hard coal is used, because its heating value (HV) is much higher than lignite there are cases where transporting hard coal to the power plant is financially viable. Such an example is in Hamburg Germany where hard coal is transported via boat from Russia around 2-4 times per week (according to demand) to be used at the Plants. [12]

In the current study, for the comparison between electricity from hydro and fossil fuels the data from Ecoinvent library have been used. An average efficiency of 52-55% has been assumed for the case of natural gas plants. This is about the efficiency that a combined cycle gas turbine is able to achieve.

Also, the data are assumed to be accurate in time and date. This means that no technological advancements have occurred during the period of acquiring the data and the date of the actual calculations via openLCA. This could also be such a case, since technologies as hydropower and fossil energy are well established and also have very long lifetimes, shown in the previous chapter.
Table 4.1: Input data openLCA 1 HPP Unit [9]

Inventory Data for non-alpine reservoir Hydropower Plant, Greece for the creation of one (1) Hydropower plant

**Unit Process raw data**

<table>
<thead>
<tr>
<th>product</th>
<th>unit</th>
<th>Comment</th>
<th>St. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>chromium steel 18/8, at plant</td>
<td>kg</td>
<td>1.82E+6 Used for the production of turbines and generators</td>
<td>1.55</td>
</tr>
<tr>
<td>diesel, burned in building machine</td>
<td>MJ</td>
<td>5.97E+7 Fuel for the construction of machinery</td>
<td>1.55</td>
</tr>
<tr>
<td>explosives, tovex, at plant</td>
<td>kg</td>
<td>5.95E+5 Used to create tunnels and galleries at the beginning of construction</td>
<td>1.55</td>
</tr>
<tr>
<td>gravel, round, at mine</td>
<td>kg</td>
<td>8.89E+8 Necessary for producing the concrete used for the construction of the dam and other building infrastructure</td>
<td>1.55</td>
</tr>
<tr>
<td>cement, unspecified, at plant</td>
<td>kg</td>
<td>1.02E+8 Necessary for producing the concrete used for the construction of the dam and other building infrastructure</td>
<td>1.55</td>
</tr>
<tr>
<td>reinforcing steel, at plant</td>
<td>kg</td>
<td>1.74E+6 Necessary for producing the concrete used for the construction of the dam and other building infrastructure</td>
<td>1.55</td>
</tr>
<tr>
<td>steel, low-alloyed, at plant</td>
<td>kg</td>
<td>4.07E+6 Used for manufacturing of tubes and pipes</td>
<td>1.55</td>
</tr>
<tr>
<td>copper, at regional storage</td>
<td>kg</td>
<td>2.96E+5 Used at electric cables transferring produced electricity</td>
<td>1.68</td>
</tr>
<tr>
<td>tap water, at use</td>
<td>kg</td>
<td>5.65E+7 Necessary for producing the concrete used for the construction of the dam and other building infrastructure</td>
<td>1.55</td>
</tr>
<tr>
<td>electricity, medium voltage, ENTSO, at grid</td>
<td>kWh</td>
<td>2.73E+7 Electricity supply for the construction of the power plant</td>
<td>1.55</td>
</tr>
<tr>
<td>disposal, building, reinforced concrete, to recycling</td>
<td>kg</td>
<td>(5.79E+7)* Recycling of reinforced infrastructure after expired lifetime</td>
<td>1.55</td>
</tr>
<tr>
<td>disposal, building, concrete, not reinforced, to final disposal</td>
<td>kg</td>
<td>(9.36E+8)* Non-enforced infrastructure left on-site at the end of the use phase of the power station. Mainly dam, tunnel, galleries</td>
<td>1.55</td>
</tr>
<tr>
<td>disposal, building, reinforcement steel, to recycling</td>
<td>kg</td>
<td>(5.88E+6)* Recycling of turbines, generators, tubes and pipes. Recycling rate assumed at 100%</td>
<td>1.55</td>
</tr>
<tr>
<td>transport, lorry &gt; 16t, fleet average</td>
<td>tkm</td>
<td>4.78E+6 Transport of materials to the construction site</td>
<td>2.62</td>
</tr>
<tr>
<td>transport, freight, rail</td>
<td>tkm</td>
<td>2.61E+7 Transport of materials to the construction site</td>
<td>2.62</td>
</tr>
</tbody>
</table>

*Numbers in parentheses indicate negative amount (recycling)
Table 4.2: Input data openLCA 1kWh of Electricity from 1 HPP Unit [9]

Input data for the production of one (1) kWh of electricity from Hydropower plant in Greece

<table>
<thead>
<tr>
<th></th>
<th>Product</th>
<th>Unit</th>
<th>Value</th>
<th>Comment</th>
<th>St. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reservoir, hydropower plant, non-alpine region, GR</td>
<td>unit</td>
<td>3.35E-11</td>
<td>Infrastructure of the storage power station producing the electricity</td>
<td>4.72</td>
</tr>
<tr>
<td>2</td>
<td>Sulphur hexafluoride, liquid, at plant</td>
<td>kg</td>
<td>3.40E-10</td>
<td>Used in electric insulation</td>
<td>2.09</td>
</tr>
<tr>
<td>3</td>
<td>Lubricating oil, at plant</td>
<td>kg</td>
<td>3.24E-8</td>
<td>Operation &amp; Maintenance for the turbines</td>
<td>2.09</td>
</tr>
<tr>
<td>4</td>
<td>Transformation, from unknown</td>
<td>m²</td>
<td>2.44E-4</td>
<td>Original area before the construction of the power station</td>
<td>3.02</td>
</tr>
<tr>
<td>5</td>
<td>Transformation, to water bodies, artificial</td>
<td>m²</td>
<td>2.41E-4</td>
<td>Area covered by the reservoir</td>
<td>3.02</td>
</tr>
<tr>
<td>6</td>
<td>Transformation, to industrial area, built up</td>
<td>m²</td>
<td>2.41E-6</td>
<td>Area covered by infrastructures other than the held-back river</td>
<td>3.07</td>
</tr>
<tr>
<td>7</td>
<td>Occupation, water bodies, artificial</td>
<td>m²a</td>
<td>3.62E-2</td>
<td>Area occupied by the reservoir</td>
<td>2.28</td>
</tr>
<tr>
<td>8</td>
<td>Occupation, industrial area, built up</td>
<td>m²a</td>
<td>3.62E-4</td>
<td>Area occupied by the infrastructure</td>
<td>2.34</td>
</tr>
<tr>
<td>9</td>
<td>Volume occupied, reservoir</td>
<td>m³a</td>
<td>1.64E+0</td>
<td>Volume occupied by the reservoir</td>
<td>1.67</td>
</tr>
<tr>
<td>10</td>
<td>Water, turbine use, unspecified natural origin</td>
<td>m³a</td>
<td>1.40E+1</td>
<td>Amount of water the turbine uses for the generation of electricity</td>
<td>1.67</td>
</tr>
<tr>
<td>11</td>
<td>Energy, potential (in hydropower reservoir), converted</td>
<td>MJ</td>
<td>3.79E+0</td>
<td>Potential energy of the water</td>
<td>1.67</td>
</tr>
</tbody>
</table>
5 Results interpretation and comparison

5.1 Interpretation of results from hydropower plant

5.1.1 Global warming potential

In the following tables the Global warming potential (GWP) from electricity production via hydropower is shown. The emissions are expressed in gram of CO\textsubscript{2} equivalent per kWh of electricity produced. (g CO\textsubscript{2}-eq/kWh). This follows the method of the functional unit that we have set at the beginning of the paper. It is one very effective and simple way to express environmental results. This also helps with the interpretation and also the comparison with other LCA studies.

The power plants that have been used in this paper for comparison are similar in size (around the 100MW installed capacity size that we set) but produce electricity with a different methodology. This is why the emissions are expressed in kWh of electricity generated and not the installed capacity.

The greenhouse gas emissions produced from the hydroelectric reference plant in North-Eastern Greece are 0,0176 kg CO\textsubscript{2}-eq/kWh. This amount is then split up into categories in order to examine what part of the plant causes the most emissions. In a case of a hydro plant it is expected that the construction phase plays the biggest role in the emissions, since after that the use is supposed to be “fuel free”. Apart from the energy needed to run the pumps during operation, the construction of the reservoir is the biggest contributor to emissions.

Depending on the size of a dam and also the location of a power plant these numbers can vary. It has also been shown in other studies that the emission results are not linear to the size of an installed plant. Meaning doubling the size of the dam or the installed capacity does not mean that the emissions will double as well. The kg of CO\textsubscript{2} per kWh are produced via a very complicated algorithm and have to be calculated in each case specifically. The problem with hydroelectric power plant installations is that most of them, mainly in Europe, are old installations with very limited available data. This means that there is some uncertainty when collecting results.
In conclusion the GWP of a power plant is influenced by many parameters, but an LCA study can help with evaluating the carbon footprint of such a plant and help with its comparison with other studies.

The GWP of the electricity generation from power plants running with natural gas of an average size of 100MW installed capacity is calculated to be 0,93 kg CO$_2$-eq/kWh [15]. This immediately shows the difference between the emissions from natural gas and how they are much greater than in the case of a hydro plant. This of course has to do with the use of natural gas as fuel for combustion and then production of steam that is used to turn the high, medium and low-pressure turbines that in turn are connected with a generator to produce electricity. Even though a concrete dam construction is not needed in a natural gas plant, the machinery and the creation of the whole plant, together with the continuous need of fuel in order to produce electricity mitigates the fact.

In the case of a power plant using lignite the emissions calculated via the openLCA software and the use of the Ecoinvent database give us the following results. The global warming potential is measured to be 1,3 kg CO$_2$-eq/kWh. This way of electricity production has the biggest amount of emissions calculated, which is around 50 times more than the case of electricity produced from hydro. Lignite is one of the most used fossil fuels and has also a very low heating value. This means that more fuel is needed to produce the same amount of electricity, thus producing a lot more emissions. Also burning fossil fuels produces significantly more harmful materials, like particulate matter for example.

Some might consider natural gas to be also in the family of fossil fuels, since it has to be extracted from the ground, but it is a very big improvement to lignite or other types of hard coal, as the results also show. Natural Gas also doesn’t produce any Sulphur.

In the following Figure 5.1 the results of the LCA are produced. This figure shows the environmental impacts in Greece from different electricity options.
The global warming potential of electricity production from hydro power can be broken down into individual factors. In the next figure 5.2 the diagram shows the main contributors of the emissions, which in turn sum up to the total amount of kg of CO₂ eq. per kWh of electricity produced from the reference plant. Mainly the operation of the plant (electricity production) as well as the construction of the dam (concrete) play the biggest role in the emissions of CO₂.
5.1.2 Acidification – Eutrophication potential

The acidification of 0.019 g SO₂-eq / kWh is mainly due to SO₂ of around 82% and NOₓ emissions of 14%. This value is significantly smaller than this of electricity production from lignite, 8.08g SO₂-eq / kWh because using lignite brings in the equation high Sulphur content and also some of the old power plants don’t have desulphurization systems.

For eutrophication the results also show a big difference in emissions. A hydroelectric power plant emits around 1.36 grams of PO₄ equivalent per kWh, where a natural gas power plant emits more than ten times this amount with 18 grams. In the case of a lignite power plant the results are far more severe. Taking data from other LCA studies into account, we can see that for a lignite PP the eutrophication potential rises exponentially to around 1.46 kg of PO₄ eq. per kWh. The main reason for these emissions is the emission of phosphates during mining.

For the study the following two figures 5.3 and 5.4 show the main contributors to the total emissions in both cases examining acidification and eutrophication. In both cases
mainly the cement for the construction of the dam as well as the electricity transformation plays one of the biggest roles in the total amount of emissions.

**Acidification emissions from hydropower (kg SO₂ eq./kWh)**

- **Main contributors**
  - Cement
  - Electricity voltage transformation
  - Treatment of waste
  - Steel production, chromium steel
  - Diesel used in building machine
  - Gravel and sand quarry operation
  - Copper production
  - Reinforcing steel production
  - Explosive production, tovex
  - Steel production, low-alloyed

**Eutrophication emissions from hydropower (kg PO₄ eq./kWh)**

- **Main contributors**
  - Electricity voltage transformation
  - Copper production
  - Cement
  - Treatment of waste
  - Steel production, chromium steel
  - Diesel used in building machine
  - Explosive production, tovex
  - Reinforcing steel production
  - Electricity production from hydro power
  - Gravel and sand quarry operation

*Figure 5.3: Acidification main contributors for hydro power*
Figure 5.4: Eutrophication main contributors for hydro power

In the Figure 5.5 a graphical representation of the results is created. It shows three main categories studied in this paper. All impacts shown are expressed per 1 kWh of electricity generated, which is the functional unit of the study. Under [GWP] is global warming potential understood, where the emissions are calculated per kg of CO₂ equivalent per kWh. With the notation AP the acidification potential is measured in grams of SO₂ equivalent per kWh. Finally with EP we measure the eutrophication potential in grams per PO₄ equivalent. Some rounding has been done in the final results in order to accommodate a more cleaner look. Also some of the Y axis values have been adjusted with multipliers in order to have all results in the same graph.

Having the results next to each other shows immediately the difference between electricity production from fossil fuels and renewable hydro power.

![Environmental Impacts for different electricity options in Greece](image)

Figure 5.5: Environmental impacts from electricity generation options in GR.
Table 5.1: openLCA results from three different cases of electricity production in Greece. Reference power plant size of 100-150MW

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Main Factor</th>
<th>Storage non-Alpine region</th>
<th>Greek Region 100MW</th>
<th>Greek Region 150MW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global Warming</strong></td>
<td><strong>Potential</strong></td>
<td><strong>Hydro Power Plant</strong></td>
<td>17</td>
<td>930</td>
<td>1300</td>
</tr>
<tr>
<td>Acidification</td>
<td><strong>g CO2 per kWh</strong></td>
<td><strong>Land Transformation and Concrete</strong></td>
<td>0,019</td>
<td>1,3</td>
<td>8</td>
</tr>
<tr>
<td>Eutrophication</td>
<td><strong>g PO4 eq. per kWh</strong></td>
<td><strong>Mainly from concrete</strong></td>
<td>0,014</td>
<td>0,18</td>
<td>15</td>
</tr>
</tbody>
</table>

**5.2 Cumulative Energy Demand**

Under Cumulative Energy Demand the following is to be understood. It is a part of the Life Cycle Assessment study. It enables to interpret and compare product systems in respect to energy criteria. This means that the primary energy demand, all energy carriers that are found in nature, will be calculated for the entire life time of the investigated product. CED is the sum of the cumulative energy demands for the production, the use and for the disposal of the economic good after its lifetime.

It can also be called primary energy consumption and has been on very important indicator in LCA studies. It is an approach used to quantify the energy content of all different energy resources taking place in this case for the electricity production. This includes all methods renewable (wind, solar, hydro) and non-renewable (nuclear, fossil). The cumulative energy demand method does not produce environmental impacts as results but creates and image of the energy resources. Those results can be used in multiple ways and various data sets.

In our case the CED of the electricity produced for the reference hydro power plant of a reservoir construction with a size of 110MW installed capacity is around 3,84MJ in oil equivalent per kWh of electricity generated. This number is acquired mainly because of the potential energy of water used in our case. The potential energy of water is constant and amounts to 3.79MJ/kWh. The remaining percentage is accounted from the
operation of the pumps, that their job is to fill the reservoir with excess water in cases that such an operation is needed. Any electricity that is used for the operation of the power plant, like the operation of the pumps has to be subtracted from the gross production of the storage plant in order to get correct results.

Since most of the data used in the paper are secondary data, meaning they are derived from inventories from Ecoinvent and also other studies, they are not 100% complete. This means that for example the operation of the pumps and their electricity consumption has not been taken into account.

In the case of a natural gas power plant, the reference Plant has the size of 100MW and is also considered to be located in Greece. The results that we get show that the cumulative energy demand of such a case has a bigger impact in comparison to the HPP. The total amount accounts to 15,27MJ/kWh.

Similarly, the Lignite Power Plant has a CED of 20,21MJ/kWh. This case is the most burdened and also follows what the literature shows for multiple cases around Europe. The use of lignite, with its very low Heating Value (16,077 MJ/kg) means that more fuel is needed in order to produce the same amount electricity that would be generated by Natural gas for example, which has a heating value of between 42 and 55 MJ/kg.

Table 5.2: Cumulative energy demand (in MJ oil-eq./kWh) of the Hydro, Natural Gas and Lignite electricity generated in Greece.

<table>
<thead>
<tr>
<th>Non Renewable (MJ)</th>
<th>Renewable (MJ)</th>
<th>Hydro Power Plant</th>
<th>Natural Gas Power Plant</th>
<th>Lignite Power Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td>Solar</td>
<td>Storage non-Alpine region</td>
<td>Greek Region 100MW</td>
<td>Greek Region 150MW</td>
</tr>
<tr>
<td>0,042</td>
<td>0,000019</td>
<td>0,010</td>
<td>0,013</td>
<td>0,021</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Wind</td>
<td>0,0037</td>
<td>0,022</td>
<td>0,192</td>
</tr>
<tr>
<td></td>
<td>Hydro</td>
<td>0,00055</td>
<td>0,0019</td>
<td>0,013</td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td>3,79</td>
<td>0,0105</td>
<td>0,036</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0,0006</td>
<td>0,0028</td>
<td>0,021</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total (MJ)</td>
<td>3,84</td>
<td>15,27</td>
</tr>
</tbody>
</table>

In the Table 5.2 above, the results of the Cumulative Energy Demand are shown. In all three cases the results are divided into categories. The main two are renewable and non-renewable sources. Under the renewable “umbrella” four categories are taken into account. Solar, Wind, Hydro and Biomass. In the three cases studied here solar and
biomass don’t contribute much for the CED. On the other side in the case of a hydro power plant, as mentioned before, the potential energy of water accounts for around 99% of the energy demand. (also shown in the Figure 5.6). The remaining 1% from the non-renewable categories of nuclear and mainly fossil is due to the electricity consumption of the pumps. In bigger dams where the pumps have to work harder to feed more water to the reservoir this amount is bigger and can account to around 10% of the total energy demand. Infrastructure also plays a role but also small in comparison to the potential energy of water.

In the case of the power plants that use fossil fuels, the results are the exact opposite. Renewable sources like water, solar and wind play a very insignificant role of around 1%. The remaining 99% cumulative energy demand of electricity generated via lignite or natural gas is from the non-renewable part.

Cumulative Energy Demand

- 1% Fossil
- 0,3% Nuclear
- 98,7% Hydro

3.79 MJ

Figure 5.6: CED from electricity Production via Hydropower, Case Greece
Table 5.3: Cumulative energy demand (in MJ/kWh) in Greece of the Hydro, Natural Gas and Lignite electricity generated.

<table>
<thead>
<tr>
<th>Non-Renewable (MJ)</th>
<th>Fossil</th>
<th>0.042</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>0.0037</td>
<td></td>
</tr>
<tr>
<td>Renewable (MJ)</td>
<td>Wind</td>
<td>0.00055</td>
</tr>
<tr>
<td>Hydro</td>
<td>3.79</td>
<td></td>
</tr>
<tr>
<td>Total (MJ)</td>
<td></td>
<td>3.84</td>
</tr>
</tbody>
</table>

Shown in the Figure 5.7 is a comparison between the three methods of electricity production, where the difference between renewable and non-renewable sources of CED is specifically shown. As explained above, both fossil fuel plants have a much bigger cumulative energy demand in comparison to hydro power.

Figure 5.7: CED results comparison between three different cases.
The results in all three cases are following the literature that was studied for the preparation of this paper. In cases of Life Cycle Assessment for various different power plants around Europe, storage hydro power plants have a cumulative energy demand of around 3,80MJ, which would be almost all because of the potential energy of water and up to 15MJ of oil equivalent per kWh in cases of pumped storage hydro plants. In the specific case of a pumped storage hydroelectric power plant, almost all of the CED is due to the electricity consumption of the pumps needed to pump the water up to the reservoir.

Table 5.4: CED results comparison between three different cases.

<table>
<thead>
<tr>
<th></th>
<th>Hydro Power Plant</th>
<th>Natural Gas Power Plant</th>
<th>Lignite Power Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td>0,042</td>
<td>15,24</td>
<td>19,95</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0,0037</td>
<td>0,022</td>
<td>0,192</td>
</tr>
<tr>
<td>Renewable</td>
<td>3,794</td>
<td>0,0153</td>
<td>0,07</td>
</tr>
</tbody>
</table>

5.3 Comparing results to literature

The results that openLCA was able to produce, as stated before, mainly consisted of data from the Ecoinvent database. In the case of a hydropower station study, data are quite scarce and also outdated. In order to verify the results a comparison with literature was conducted. The literature in question was other different European studies about mixed electricity production options. In the following two figures, 5.9 and 5.10 the comparison of the results is presented.

The main bars show the results acquired from a study made in Turkey where all available energy methods were assessed. The impacts in question are global warming potential, acidification and eutrophication. The black bars are a European upper and lower limit. These average numbers have been produced with comparing and also averaging the results of different studies across Europe.

In order to get the average results for the European union 12 studies were included. For the hydropower 5 of those studies were about dam-reservoirs and 7 with run-of-river plants. Most of the emissions were generally linked to the infrastructure of each project. In the case of dam-reservoirs there is an important aspect in each study, mainly the
methane emissions because of the decomposition of flooded organic matter. This happens because of the land transformation where a dam is created. All of these results also depend very much on the size of the infrastructure (size of dam and water depth) as well as the kind of flooded vegetation and soil type. Climate also is a big factor.

Finally, emissions for NO\textsubscript{x} and SO\textsubscript{2} were caused because of the dam construction, which means that those emissions are related to the size of the project and the generation capacity of each plant.

With the red dots the results of this study are presented. As we can see all of the results that the openLCA software produced are well within the European range of the available literature. This helps with assessing correctly the environmental impact of the reference power plant. There is always some error when doing an LCA because of the very big input inventory, but the results in this case have been in order.

![Results from hydropower](image)

*Figure 5.8: Comparing results to literature, hydropower. [13]*
5.4 Advantages of electricity production from RES

They are virtually inexhaustible sources of energy and can help reduce our reliance on conventional energy sources like coal. They usually have low operating costs which are also more importantly not affected by fluctuations in the international economy or politics at a given time. RES investment creates a significant amount of new jobs, especially at the local level. Finally, they are as we have mentioned many times environmentally friendly and their use is generally accepted by the public.

Hydroelectric power stations can be switched on as soon as possible when additional electricity is requested, which cannot happen with thermal stations (coal, oil) which require preparation for startup. Hydropower is also a domestic source of energy and contributes to the strengthening of energy independence and the security of energy supply on a national level. Many have said that it can be the nucleus of revitalization.
economically and socially of forgotten areas and can also contribute to local development through investments.

5.5 Disadvantages of electricity production from RES

On the other hand, renewable energy sources, and production via hydro have some significant disadvantages. Mainly they are quite scarce in energy density, that’s why extensive facilities are required to produce the same amount of output energy. The investment cost per unit of installed capacity compared to current conventional fuel prices is still significantly high.

Drawbacks of a hydro power plant installation are mainly the initial costs of building dams and equipment for the station in order to produce the electricity. The projects usually also have a very long duration until completion. There are cases of strong environmental alteration of the reservoir area, possibly population shifting and land use change. The new idea is to try and create more small dams which would accommodate smaller hydro plants but would help avoid all these risks.

In a hydropower installation the main drawback is also the emissions produced from the soil under water because of inundation. Because at every new construction where a dam is created the surface changes very significantly, all those changes have their own effect on the environment. The soil contains organic compounds that are slowly broken down and then released into the atmosphere. These carbon compounds are then broken down to CO\(_2\) or simply carbon dioxide. This happens with the help of the acid in the water. The biggest impact occurs during the construction of such a big installation. After that the effects are quite minimal, only due to the operation and the maintenance of the site.

5.6 Alternative ways to produce electricity

5.6.1 Solar-Wind Energy

There are many other ways to produce electricity. Studies show that the way of the future will be renewable energy sources. The main idea is to try and decouple from the need of fossil fuels for the future. Fossil fuels are easy to use, the infrastructure is already there, and technology has somewhat improved during the years, but there is no doubt after so many studies that industry and powerplants are the main reason of global
warming and the change of the Earth. The way to change is to try and rely more on renewables but also find a way to make them more efficient.

The problem with renewable energy such as solar, wind and some cases hydro are that they are not always available. Also, when they actually become available, sometimes they are not all exploited to the maximum. In order to achieve more with renewables and to integrate them more in the everyday system there is need for an efficient way to store energy when it is available in order to use it when renewables cannot produce, like during the night, when the weather is not good or there is not enough water.

One of the main ideas for storage has been the use of batteries. This means converting the energy that is available and not used into chemical energy and storing it in batteries. There are such solutions already, but most are quite expensive and not that efficient.
6 Conclusions

To assess the sustainability of an energy system, the environmental indicators must be investigated. Global warming is the first indicator that comes to mind, but there are other important ones as well. In this study the environmental impacts throughout the life of a hydro power plant have been evaluated conducting a process-based life cycle assessment.

Greece has the potential to produce electricity from many different sources, including lignite, natural gas, solar and in our case hydro. [7] After accessing the impacts from the categories selected, it is shown that the hydropower energy option has a lower effect as an option in electricity production compared to other traditional non-renewable options such as lignite and natural gas.

In this current study it is shown that lignite has the highest impacts for the three categories selected. Gas power comes second with some categories being similar to lignite but performs better because of the smaller amount of Sulphur in the natural gas used as the main fuel. In cases where a non-renewable fossil power plant is used in a combined way, producing electricity and useable heat the results may become better but still it performs worse than a hydro power plant [14].

The results from this study have shown that electricity production from renewable sources, in this case hydro, is better and less impactful for the environment compared to old fossil fuel technologies. It was a result that was expected, since taking into account a long-life use of such a construction, having the ability to use a fuel that is simply free, immediately mitigates the impact during the construction phase. In a next paper maybe just the renewable options (solar, wind, small hydro) could be studied in order to access which one of these would be the new technology to follow for the future.

Taking the results of the cumulative energy demand (CED) into account as well, we have another indicator of how a renewable source like hydro power functions. In the case of the lignite and natural gas plants, the CED is much higher and depends almost fully to non-renewable elements, whereas in the case of hydro electricity production the main part of the CED is because of the potential energy of water itself.

Finally, the main problem with such studies is that the LCA tool is quite new for Greece, which means there are not that many similar studies, examining the impact of different pollution mechanisms. Combined with the fact that many storage hydro plants are old, and the available data is minimal or either missing, means that while the results
have an impact and show a picture about how electricity is produced and its effect on the environment, there is still much room for improvement. Together with the literature reviewed in this paper, it is quite clear that there is a significant variation of results depending on the location of the study. What the results show though is that they can be actually taken into account in the decision-making process, when there is consideration for a new development of a new electricity project.

Finally, it is worth mentioning that in the case of a hydro plant there are other important factors to consider that were not available in this study because of lack of data, such as water continuity, quality, supply of nutrients as well as their transport but also the need for people to relocate because of the construction of the dam and in hindsight the flooding of the area. Future studies should be done in order to balance these kinds of projects in terms of sustainability.
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Appendix

1. Software representation of power plant in openLCA software
3. Natural gas power plant, 100MW installed capacity

<table>
<thead>
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<th>Inputs</th>
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<td>electricity, high vo...</td>
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<table>
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</tr>
<tr>
<td>water, decarbon...</td>
<td>water, decarbon...</td>
</tr>
</tbody>
</table>
4. Lignite power plant, 100MW installed capacity
5 Graphical results obtained from openLCA software about three impact categories

- Global warming potential
- Acidification