AKADEMIA GÓRNICZO-HUTNICZA IM. STANISŁAWA STASZICA W KRAKOWIE
**WYDZIAŁ ENERGETYKI I PALIW**

KATEDRA ZRÓWNOWAŻONEGO ROZWOJU ENERGETYCZNEGO

# Praca Dyplomowa

## *Energy Storage to Stabilize Electricity Grid Operation*
## *Magazynowanie energii w celu stabilizacji działania sieci elektrycznej*

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## Abstract

Currently fossil fuels dominate the energy sector; they are inexpensive and consistent at meeting the energy demand required. While renewables become a major player in energy supply, we are faced with the important question of whether the volatility of renewable energy sources such as wind and solar can meet the growing requirement for energy that is needed today. As every country around the world faces the energy crisis at hand while maintaining its devotion to carbon neutrality, the solution to consistent energy supply is explored. Energy storage, a concept that has been used by power plants for years to avoid energy waste and maintain grid parity. Small scale, household storage systems can be considered but as cities grow and more than 50% of the population living in urban areas with no space, large scale energy storage systems are required to maintain stability and consistency in the grid.

## Summary

Many different types of energy storage systems can be examined as major players in regulating and stabilizing the energy grid that currently is encountering many concerns. As the EU directives continue to encourage users to transfer to Renewable Energy Sources (RES) the issue of strengthening the infrastructure currently in place to allow for short term and long-term energy needs to be met. In this work I will present the possible changes Poland can make in installing new and retrofitting existing infrastructure to provide much needed stability to the energy grid. Providing solutions for energy storage such as PHES, CAES, LI-IO Batteries, and Hydrogen Storage are critical in strengthening and stabilizing the energy grid in Poland, by allowing for energy to be stored in ways where it is readily accessible when needed if user energy demand peak and fluctuate. Focusing on these four different types of energy storage systems and their capabilities along with economic and feasibility in using these types of systems in Poland. I will propose new locations and approach to installing new Pumped Hydro Electric Storage facilities, that will facilitate and strengthen the electric Power grid in Poland.

# 1. Introduction

The use of raw materials and energy sources dates to ancient times, being a primary component in human life. The Energy Sector first started to become established in the early 1950s when the French foreign minister proposed the ECSC (European coal and Steel Community), where the first steps toward energy consolidation was made allowing there to be a common market for coal and steel. Also promoting the modernization and profitable development of European Coal and Steel Industries. Later in 1957, the Euratom (European Atomic Energy Community) Treaty, where again the goal was to enhance Europe's Energy independence during the times of the Suez Crisis where Europe's oil supply was threatened. Followed by the market liberization in 1987 Europe began where the Single European Act (SEA) removed barriers allowing competition among operators and separation of energy production, transportation, and distribution activities; where each member state remained decision makers in determining their own energy mix [1]. At the turn of the century, the issue and awareness of Global Warming took the spotlight and widespread initiatives began to form, the issue at hand was one that is a staple in today's society, the alarming rate at which earth's temperature is increasing. Global warming occurs when Carbon Dioxide and other air pollutants are trapped in the atmosphere and absorb sunlight/solar radiation that have bounced off the earth surface causing heat to be trapped, the pollutants such as CO2, methane, nitrous oxide etc., are not easily broken down and loom in the atmosphere for up to centuries. Although this is not the only issue, as these harmful toxins remain in the atmosphere humans, animals and all living things are adversely affected, causing cancer and other detrimental health effects. These global warming inducing gases and effect is called greenhouse gases and the greenhouse effect respectively. This triggered a rapid and demanding change to the energy sector. In 2005 a carbon market was founded, and industrial sectors were penalized for the overuse of harmful fossil fuels. To diminish the number of fossil fuels while still maintaining the required supply of Energy to consumers, the industrial sector began to transition their fossil fuel heavy power plants into green renewable energy sources. Thus, bringing to light energy transition. Energy transition first brought the energy climate package, with the goal of reducing greenhouse gases, improving energy efficiency, and increasing the share of renewables all by 20% by 2020; this proved to be much more challenging than expected and the goal was not reached. Finally, during COP 21 in Paris 196 Parties adopted and accepted the terms of the Paris Agreement, to limit the global warming to well below 2 Degrees Celsius. Then the EU adopted the green deal, where Europe would reach Carbon Neutrality, by reducing the emissions of Greenhouse Gases by 55% (in comparison to 1990). Carbon Neutrality means having a balance; no longer emitting more than can be absorbed from the atmosphere. Per the UN " The term (Net Zero) is becoming a rallying cry, frequently cited as a necessary step to successfully beat back climate change, and the devastation it is causing" [2]

Today, consumers view energy as a prerequisite to everyday life, making producers essential. Throughout the 1990's in Poland coal delivered 95% of the electricity annually. As the economy strengthened and grew throughout the early 1990's, electricity demand also spiked, increasing from 132 TWh to 164 TWh. Energy availability and cost is key when it comes to economic growth [3], however the dependency on coal in Poland has started to cause serious local and global environmental threats and needs to be remedied.

**Figure. 1.1** Belchatow Power Plant in Poland, one of the most polluting coal power plants in the EU in 2018

*Source:Compiled from [4].*

Poland’s electricity production amounted to 157.7 TWh in 2020, of which hard coal and lignite accounted for 70%. Although Poland still significantly relies on power production from hard coal and lignite, 70% is a significant decrease from the 79.5% supplied by the later in 2018[5]. Poland’s Energy policy (PEP2040) set the basepoint for the energy sector in Poland, setting goal requirements such as i) a Maximum 54% share of coal fired power generation (ii) minimum of 23% renewable electricity in final consumption (iii) nuclear power ramp up by 2033 (iv) reducing greenhouse gas emissions by 30% (v) reducing primary energy consumption by 23% [6]. Although the 2020 goal of 20% RES was not met, there is a significant increase in electricity production by RES amounting to about 15.4% and with the new 2040 goal looming, the energy sector is beginning to progress. Carbon neutrality by 2050 means Poland will focus on many aspects to reach and maintain net-zero emissions by sustainably growing and increasing efficiency and competition within the energy sector.

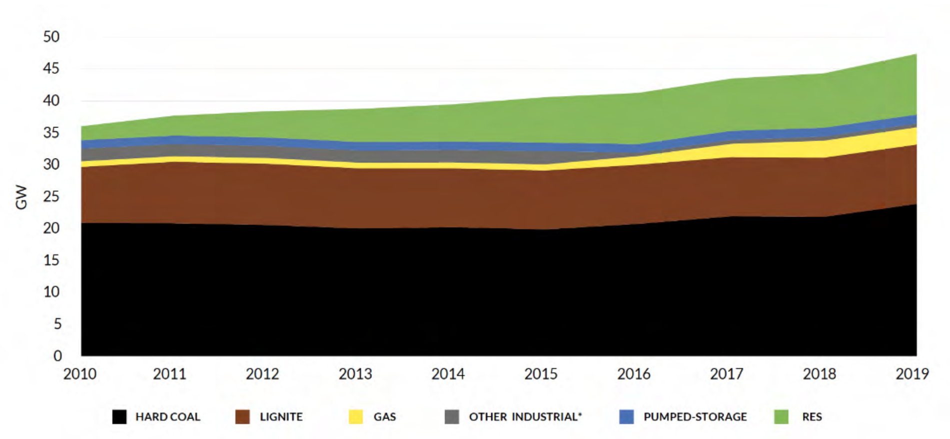


**Figure. 1.2** Energy Production in Poland varying from 2010 to 2019

*Source: Compiled from [7].*

IEA forecasts that by 2026 Renewable energy capacity will rise 60% from the 2020 levels [8]. Although the initial costs for materials and installation are fairly high the newly increasing fossil fuel costs allow RES to be a competitive source of energy. The most common RES are wind and solar, but these energies are very volatile and cannot be heavily relied upon when it comes to a consistent energy supply; the supply and demand fluctuations happen at opposite times, I.e. day and night respectively. Table 1.2 below shows the break-down of the amount of energy supplied by each listed resource in 2019, wind supplied 15.1 TWh, while Solar only supplied 0.7 TWh.

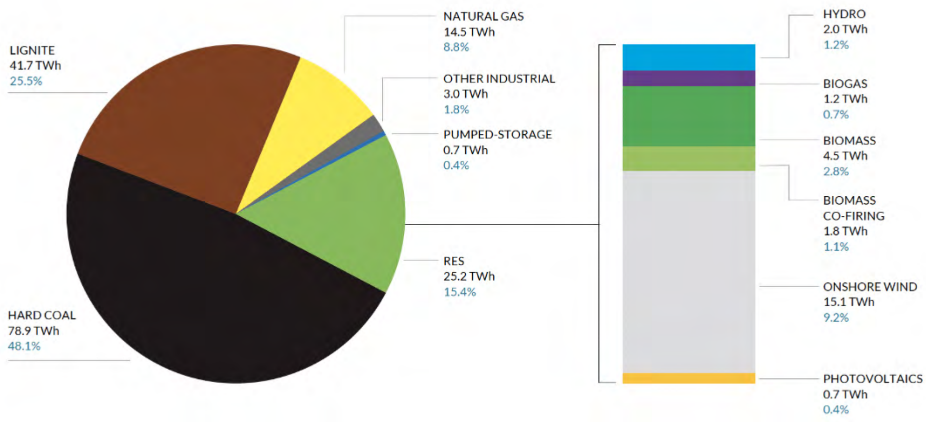


**Figure. 1.3** Energy Production in Poland in 2019
*Source: Compiled from [7].*

The Energy sector is mainly controlled by four companies: Polska Grupa Energetyczna (PGE), Tauron Polska Energia, Energa, and Enea. All of which have the same goal, increase production of Renewables and to provide a security blanket to their customers in the form of energy Storage. Respectively, PGS, Tauron, Energa, and Enea stipulated they will provide 800MW [9] , 160kWh [10]at27MWh [11], and **. Poland being highly reliant on easily dispatchable and invariable Coal to produce Energy for decades raises a red flag to consumers who are unsure that an easy transition can be made. It is essential to increase the numbers and capacities of Energy Storage Systems (EES) in the form of Pumped Hydro-electric Storage, Compressed Air Storage, Hydrogen Storage and Batteries for Storage. In this work the capacities, capabilities, and economic effects of implementing different storage systems in Poland will be examined. Using TIMES Energy modeling helped to showcase how to implement different types of storage over a rolling horizon, over a time period greater than 48 hours.

## 1.1. Wind and Solar Energy

Wind energy is a feasible option when it comes to supplying energy, and it is essential to maintain and increase the RES supply of energy in order to reach carbon neutrality. Currently one of the largest Wind Farms, Karscine Wind Farm is in West Pomerania and has an installed capacity of 90 MW, and there are many new plans to construct on and offshore wind farms throughout Poland.

Nevertheless, there are some unfortunate cons of wind, a main one being it is sporadic and cannot be controlled. The energy produced is completely dependent on the weather which causes variations hourly, resulting in challenges for grid operators who are used to consistent dispatchable energy. These fluctuations in generation impact the day-ahead etc. operating procedures.

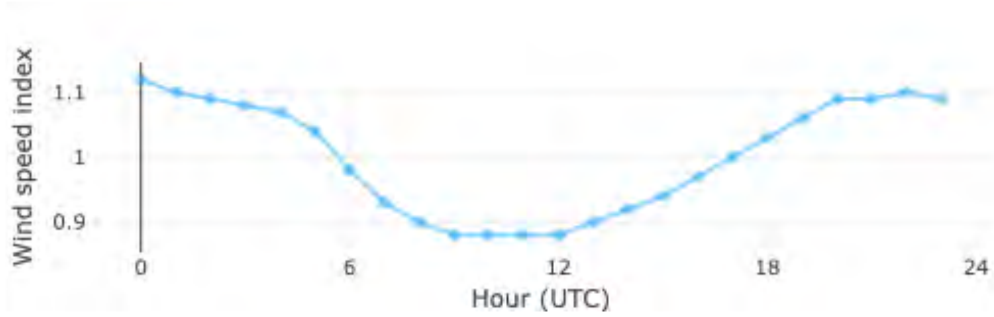


**Figure 1.2** Wind Speed in Lower Silesia Poland on an Daily Basis.
*Source: own elaboration.*

Solar energy has the largest installed capacities in Poland as they are simple to institute and the can be installed anywhere. However, the infamous "duck curve phenomenon" brought to light the issue that lies with large PV installations. The Duck curve coined in 2013 by a California Independent System Operator in the USA, essentially shows how instable the grid can be throughout different peaks and falls throughout the day. This curve shows 2 high points of demand and one very low point of demand, and the ramp up between them being extremely sharp. See figure 2.1 below for a visual representation of a duck curve.

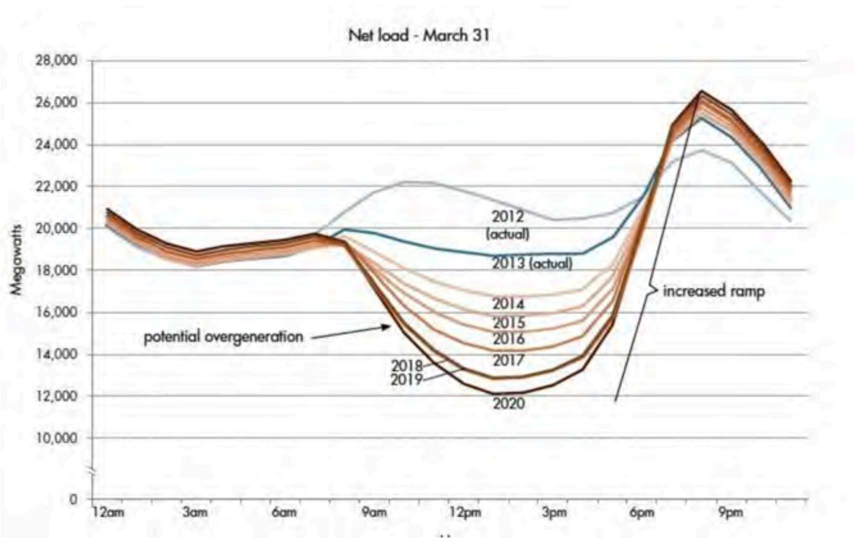


**Figure. 1.3** Duck Curve by California Independent System Operator
*Source: Compiled from [12].*

Solar energy often peaks during the day and once the sun sets power plants need to quickly ramp up to pick up the demand, while during the peak hours there is an over generation of power where the PV systems make more energy at one time than can be consumed [13]. Storage Facilities such as Pumped Hydro Electric Storage, Compressed Air Storage, Batteries, and Hydrogen are essential to flatten these fluctuations and stabilize the energy grid.

## 1.2. Integration of Storage Technologies with RES

Energy Storage technologies have been around for decades but have been relatively undeveloped in Poland before 2010. It consisted of a spectrum of non-standardized technologies or EES technologies, of which there are four main families: mechanical, electrical, chemical, and electrochemical storages. These storage types cater to the different requirements of energy needs, ranging from an hour-day scale to a monthly. These storage systems based on their capacity, duration of discharge and costs of electricity generated are segregated.

When considering types or storage technologies locations are essential, large-scale technologies such as pumped hydro-electric storage, hydrogen storage, and compressed air storage require integration of fields, based on these the capacity is limited. While smaller scale or modular forms of energy storage such as Batteries can be designed to fit any given location. Figure 1.4 below represents the rated power, energy content and discharge time of various types of Energy Storage systems. From this it is apparent that PHES, CAES and Hydrogen are advisable for longer storage periods, on a day-month scale while the lower rated technologies can be considered for min-hourly use at a smaller scale.

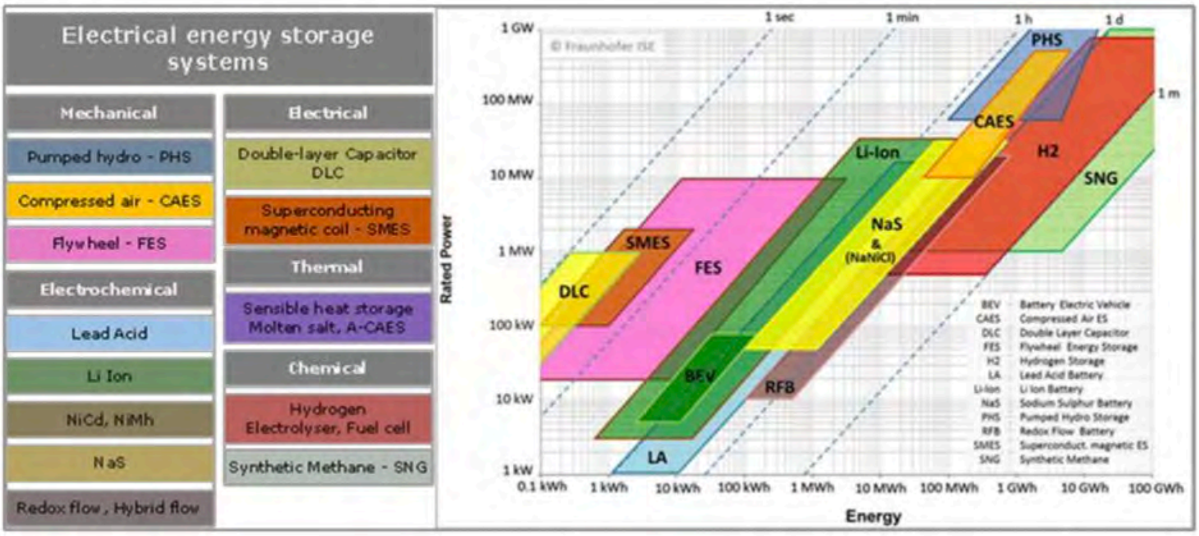


**Figure. 1.4** Various Electrical Energy Storage Classifications and Performances
Source: Compiled from [14].

In 2021 the Energy Policy was adapted to remove regulatory and legal barriers from energy storage systems. This new amendment allows the development of EES to flourish. In this work, I will focus on examining 4 main energy storage systems represented in Table 1 below.

**Table 1.1.** Characteristics of selected Energy Storage Technologies.

| | Max Power Rating (MW) | Efficiency | Discharge | Lifetime | Energy Density (Watt-hr per L) |
|---|---|---|---|---|---|
| **PHES** | 3000 | 70-85% | 4h-16h | 30-60 yrs | 0.2-2 |
| **CAES** | 1000 | 40-70% | 2h-30h | 20-40yrs | 2-6 |
| **Li-Ion Battery** | 100 | 80-90% | 1min-8hr | 1000-10000 cycles | 200-400 |
| **Hydrogen** | 100 | 25-45% | Mins-week | 5-30 yrs | 600 (@200bar) |

*Source: Compiled from [15].*

# 2. Storage Technologies

In this chapter this work will explore different types of technologies and their capabilities for adoption into Poland's energy sector.

## 2.1 Pumped Hydro Electric Storage

Pumped Hydro-Electric Storage (PHES) currently accounts for 99% of the energy storage capacity in the world. It is one of the oldest EES Systems, being in Poland since the early 1900's. Consisting of an Upper and Lower Reservoir, PHES Systems can be easily integrated with other renewable energy sources making it an integral aspect to long-term energy storage. During the daytime hours when Solar/ Wind energies (etc.) are at peak supply and energy is in lower demand the water is pumped from the lower reservoir to the upper through a penstock using a pump and then inversely is released back down through the penstock into a turbine during high energy demand times. There are two common pumped hydroelectric storage systems, a open-looped system where the lower reservoir is connected to a naturally flowing body of water, typically a river; and a closed-loop system where the upper and lower reservoirs are 2 closed entities not connected to any flowing bodies of water.

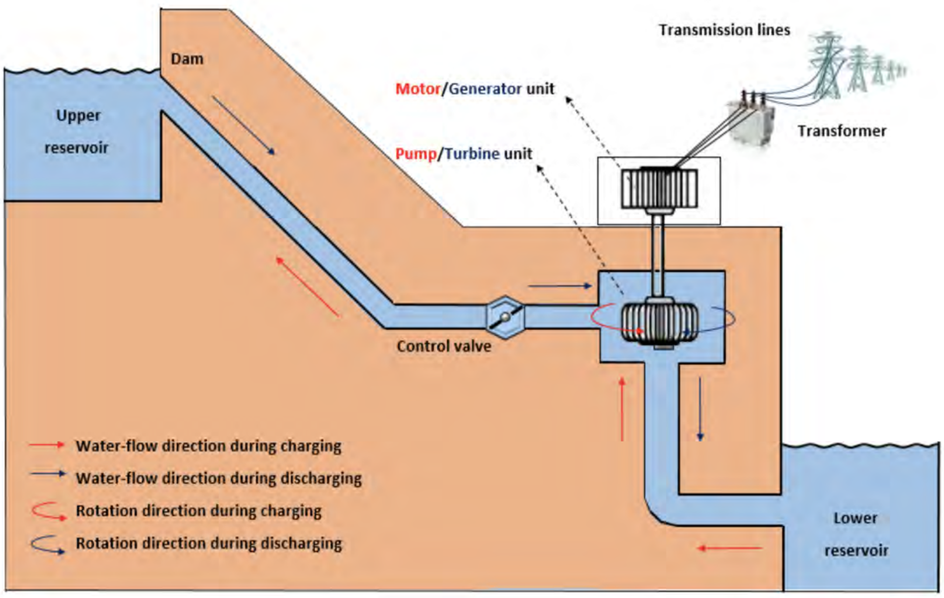


**Figure. 2.1** Schematic of a typical Pumped Hydro-Electric System and its operation

*Source: Compiled from [16].*

Europe’s largest Pumped Hydro-Electric Storage Systems is in Italy with the total installed capacity of 7685 MW. Norway also has a very high development capability for PSP, with a lot of available and suitable terrain; 10th in the world Norway has a capability of storing nearly 87 TWh of energy storage, with 10-20 TWh of available capacity every day.

**Table 2.1.** Existing PHES Systems in Poland and their Capacities

| No. | Name | Location | Head (m) | Capacity (MW) |
|---|---|---|---|---|
| 1 | Dychow | Lubuskie | 30 | 79.5 |
| 2 | Solina | Solina | 60 | 200.2 |
| 3 | Czorsztyn-Niedzica | Malopolskie | 46.1 | 93 |
| 4 | Porabka-Zar | Slaskie | 439 | 500 |
| 5 | Zarnowiec | Pomorskie | 119.3 | 680 |
| 6 | Zydowo | Wielkopolskie | 81 | 150 |
| Total | | | | 1713.7 |

*Source: Compiled from[17].*

Many important aspects need to be taken into consideration when it comes to location and construction requirements of a new PHES System. There is an existing structure that presents different topologies and their capabilities; See below for the explanation of topographical and technical requirements of PHES, all of which are requirements when choosing an ideal location. Improving the area topography (shape) while also pin-pointing new PHES Systems using existing rivers etc. Rivers are a sought-after commodity in this instance as they diminish the need for a lower reservoir.

Types of topologies for PHES System Operations on an existing to be reused basis or instance where there is availability to rely on naturally occurring dams/ reservoirs can be considered:

(i)Topology A- One reservoir exists (low elevation) and a new higher reservoir is constructed (all equipment etc.)

(ii)Topology B- Two reservoirs already exist (all equipment, piping etc. to connect) (iii-vii) T3: (2) new reservoirs, T4: new upper, lower is sea, T5: Multi-reservoir. Converted, T6: river connected to upper res., T7: abandoned mine connected. To reservoir/ lake.)

Many other important requirements and assumptions are listed below for PHES:

- Assumptions: All dam types can be considered, no matter their construction can be concrete, sed. Rock etc.
- Distance between reservoirs
- Required Head (absolute distance between upper and lower water levels- the higher the greater power output)
- Min. Slope (ratio of hydraulic head to horizontal distance between upper and lower res.)
- Maximum slope
- Volume and Surface of new reservoir

**Table 2.3.** Existing PHES Systems and their topographical aspects in Europe

| Study | Maximum Distance (km) | Minimum Fall Head | Minimum Reservoir | Minimum Hyd. Slop | Maximum Area Slope |
|---|---|---|---|---|---|
| **K.P. Consulting** | 5 | -- | 3GWh | -- | -- |
| **Connoly et. Al.** | 1 | 200/150 m | 12/18 ha. | -- | -- |
| **Wickramarathna** | 10 | 400m | 1500 Gwh | 0.1 | -- |
| **Schaefer et al.** | -- | 100m | -- | 1.8 | -- |
| **Fitzgerald et al.** | 5 | 150m | 7 ha | -- | 3-7 deg |
| **Lacal Arntegui et.al.** | 1-20 | 50/150 m | 0.7 ha | -- | 5% |
| **Hall and Lee** | 3.2 | 6.1 m | 40.5 ha | -- | -- |
| **Kukukali** | 10 | 200 m | -- | 0.1 | -- |
| **Lu and Wang** | 10 | 500 m | 6 ha | 10% | -- |

| | | | | | |
|---|---|---|---|---|---|
| **Soha et al.** | 5 | 50 m | 35 MWh | 0.1 | 5-7.5 deg |
| **Lu et al.** | -- | 300 m | 1 mio. M | 1:15 | -- |
| **Ghorbani et al.** | 20 | 150 m | 7 ha. | -- | 5% |

*Source: Compiled from[18].*

Poland currently has a installed capacity of 2,187 GWh of Hydro-Power Generation and the total electricity generation of about 158,551 GWh this being said it accounts for only 1% of the energy generation. Due to the difficult situation and fast changing pace of the energy sector, increasing the hydroelectric potential is a favorable as although it has a high CAPEX initial cost, it proves its self-worthy with the high efficiency and balancing load capabilities. It is also considered to be economical in its on-peak and off-peak prices.

## 2.2 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) plants work by compressing air during low demand/day-time hours and storing it in a storage tank/ facility and then releasing the compressed air to power. A turbine of sorts during high demand times. Compressed air can be stored in above ground Steel Tanks, or, more commonly, underground storage systems (man-made or existing salt caverns etc.) CAES Plants are very rare in Europe and there are only a few active today world-wide. One being the Huntorf plant in Germany can produce up to 290MW of power.

**Table 2.4.** Existing CAES Systems and their characteristics.

| Facility | Operator | Year Operational | Power [ MW] | Discharge time (hr) | Efficiency | Pressure | Cavern Type |
|---|---|---|---|---|---|---|---|
| Huntorf, Germany | Uniper Kraftweke | 1978 | 290 | 2 | 29% | 48-66 | Salt Cavern (doub.) |
| McIntosh AL, USA | Power South Eneeregy | 1191 | 110 | 26 | 36% | 76 | Salt Cavern (single) |

*Source: Compiled from*[19]

Currently in Poland there are many possibilities to construct new CAES Plants, in areas such as central Poland where there are existing salt caverns that are at the ideal depth of 105 to 475 m deep below ground level. Also, as the actual space requirement is fairly small, installing above ground compressed air storage tanks is also a possibility.

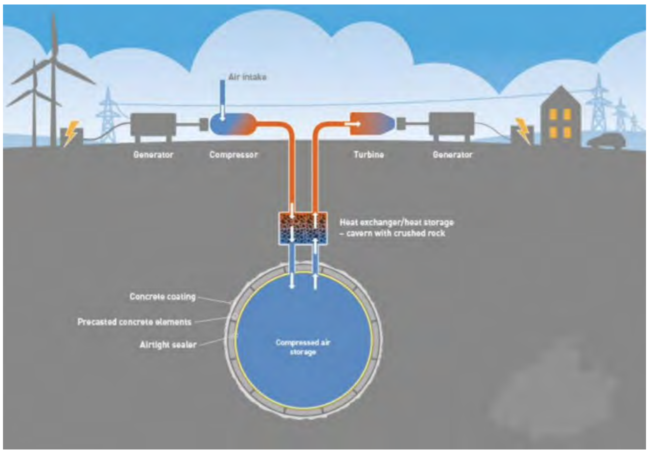


**Figure. 2.3** Schematic of a typical Compressed Air Energy Storage System and its operation

*Source: Compiled from [20].*

Compressed Air Energy Storage is a viable candidate of energy storage to stabilize the electric power system operation, as they have a fast response time (dispatchable).

## 2.3 Battery Storage

Batteries provide a very condensed form of energy storage by converting electrical energy to chemical energy. Battery storage is a concept that has been around since the 1800's and is currently used in many sectors.

**Table 2.5.** Existing Battery Storage Systems and their characteristics

| Place | Co. | Capacity | Type of Battery | Use |
|---|---|---|---|---|
| South Australia | Tesla | 100MW/129MWh | Li-Ion | Wind Farm |

| | | | | |
|---|---|---|---|---|
| Germany | STEAG's | 90MW/120MWh | --- | Battery Storage Project |
| Italy | Terna | 38.4MW/250MWh | Sodium Sulphur | Wind Power |
| Japan | NGK | 34MW/204MWh | Soduim Sulphur | Wind Power |
| USA, California | AES-SDG&E | 30MW/120MWh | Li-Ion | --- |

*Source: Compiled from*[21]

The Energy Sector in Poland (Tauron, Enea, PGE and Energa) is currently developing plans to increase storage in the form of batteries. Standard batteries consist of two terminals called the cathode and anode; When electrons move from the cathode to the anode the chemical potential energy is increased in turn charging the battery and inversely when moving in the opposite direction the chemical potential energy is converted to electricity in the circuit and is discharged.

**Figure. 2.5** Energy Storage in the form of Large Scale Batteries.*[22].*
*Source: Compiled from [21]*

## 2.4 Hydrogen Storage

Currently in Europe Hydrogen only accounts for 2% of Europes energy consumption, of this a majority of the Hydrogen production is through natural gas which still results in significant amounts of CO2 emissions. However, as the energy sector transitions to renewables, different forms of Hydrogen can be captured and stored for long periods of time. Specifically green hydrogen is a hot topic when it comes to decarbonizing the industry, mobility, electricity system etc. by substituting the energy from fossil fuels [23].

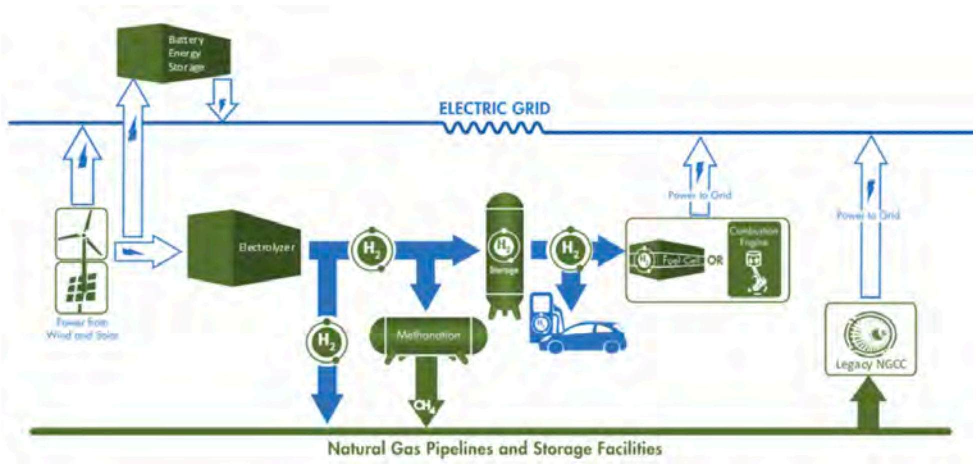


**Figure. 2.6** Hydrogen Energy Storage Operation
*Source: Compiled from[24].*

# 3. Aim and scope of the thesis

The aim of this thesis is to propose locations of new large-scale energy storage systems in the form of Pumped-Hydroelectric storage in Poland. Taking into consideration the large and diverse footprint of Poland this research will present pre-determined technical factors as well as the geographical capabilities in the Lesser Poland and Pomeranian Voivodships. The following methodologies will be used to establish optimal locations and storage capabilities/ capacities. These capacities include location, socio-technical factors, ecological factors, as well as size and shape for optimal energy storage in the selected regions. Due to the energy crisis, these locations are crucial to begin the process of constructing Storage systems to provide stabilization to the electricity grid. This thesis will present optimal locations for PHES and their capacities based on data collected about Poland's energy consumption. Energy demand must be met and provide a consistency required to be self-sufficient without reliance on other European countries and fossil fuel heavy Power Plants, to reach carbon neutrality by 2050.

Therefore, the research topic will shed light upon the following questions:

- What topographical and physical restrictions drive the location of PHES?
- What methodology determines optimal PHES location?
- What existing information is required to optimize size and location of PHES?
- What location provides the optimal storage capacity and energy production?

# 4. Methodology

QGIS is a Geographic Information Systems Software, that is very commonly used to analyze topography for energy storage systems. Using QGIS an algorithm was developed for the installation of a PHES by implementing the rules and regulations required, and a topographical analysis was done to understand the theoretical potential and physical restrictions required. After these criteria are established the Analytical Hierarchy Process (AHP) is used to rank the criteria and determine the top five most essential factors that will be isolated and then overlayed in QGIS and using the buffer tool, four locations will be taken in each voivodship. Following this using a simple calculation and assumptions based on the size of the existing body of water or lower reservoir, which is found in QGIS, the sizes and power outputs for a new man-made upper reservoir will be presented.

## 4.1 Pumped Hydro Electric Storage Criteria Selection

To begin the process of finding an ideal location for PHES in Poland, a detailed examination of existing conditions and feasibility based on requirements was conducted. As QGIS requires a high computational load and files are very large to accommodate all of Poland, areas with the highest PHES capabilities need to be identified. As Figure 4.1 presents the Lesser Poland and Pomeranian regions have the potential for new PHES that can be 300 TJ or more.

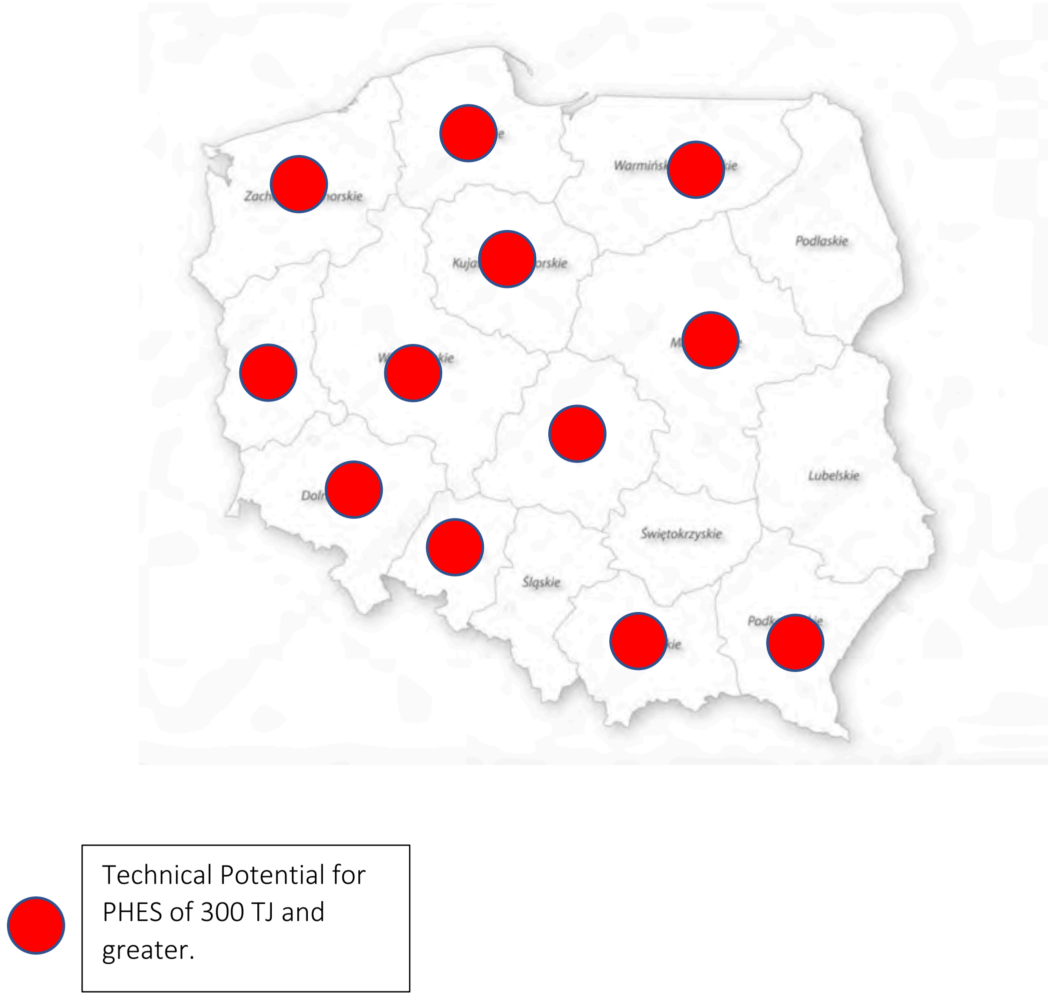


**Figure. 4.1** Diagram of technical potential of PHES in different regions of Poland.
*Source: Compiled from [17].*

As mentioned in Chapter 3.1, this study will be focusing on finding and pin-pointing areas that correlate with Topology A, locations with an existing lower reservoir will be considered. The algorithm that was used to optimize this process is presented in the following chapters.

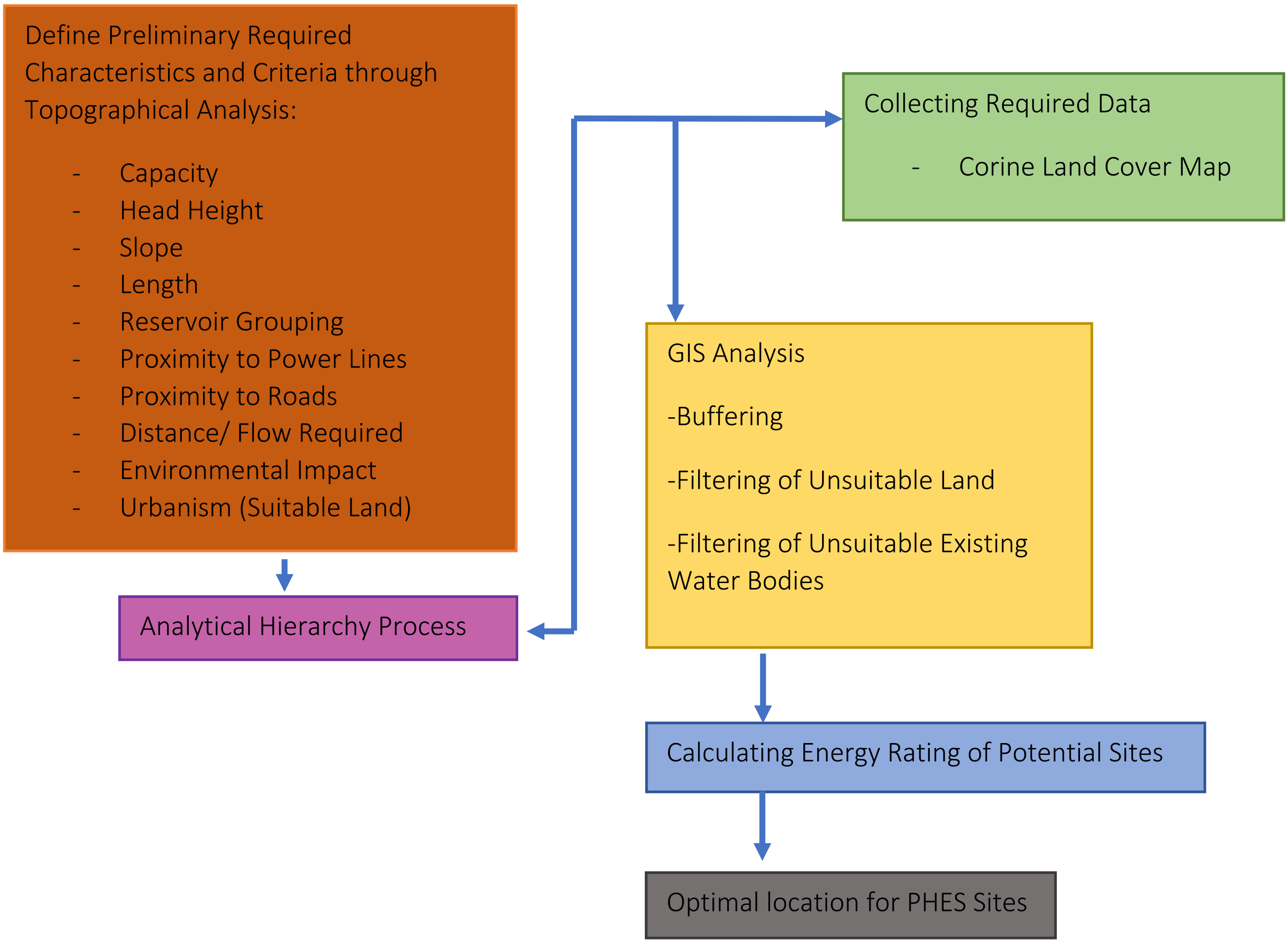


**Figure. 4.2** Schematic of Algorithm

*Source: Own elaboration.*

As mentioned in the methodology, to further the decision-making process of acceptable PHES sites within the selected regions a combination of AHP, QGIS Processing, and calculations via excel were used, further expanded in the following chapters. This process is essential to finding the available sites, as many areas cannot be considered due to several environmental and physical requirements. Figure 4.3 is an example of the typical process followed when selecting a suitable site for the construction of a new upper reservoir.

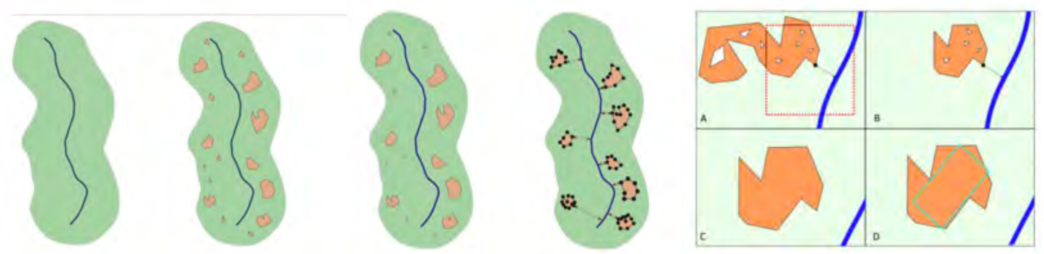

**Figure. 4.3** Schematic of process of pin-pointing preferred location of PHES
*Source: Compiled from[18].*

### 4.1.1. Potential Location

Establishing the optimal location with theoretical potential to build an upper reservoir, focusing on the selected and researched regions where existing waterbodies are available and reach the requirements outlines in chapter 4.3.

## 4.2 Criteria Selection to Theoretical Potential

The top ten criteria were extracted. Based on the research and expert opinions the most important aspects are as follows in subchapters 4.31 through 4.3.10.

### 4.2.1 Capacity

Capacity in this situation is referencing the capacity of existing natural occurring bodies of water. The analysis will be processed on existing natural occurring bodies that have the potential to be lower reservoirs.

### 4.2.2 Head

Head is simply the height at difference between where water enters the PHES system and where it exists the system. In the model and analysis created the head will be calculated between the location of existing body of water and the new potential location available for a man-made reservoir.

### 4.2.3 Slope

Slope is calculated based on the topography of the land at hand and its rise or fall. This is a critical criterion when referring to PHES location as there is a minimum slope required to meet the required flow/ power production.

### 4.2.4 Length of Penstock

Penstocks in PHES systems are a group of pipes that carry pressurized water and connect the upper reservoir to the turbines in the system. The length of these is typically dependent one the slope of the topography where the system is located.

### 4.2.5 Reservoir Grouping

Reservoir grouping refers to whether or not there is an existing upper and lower reservoir available. Although an important detail when designing and identifying an ideal location, this work will focus on the use of an existing lower body of water and construction of a new upper reservoir.

### 4.2.6 Proximity to Power Lines

Distance from the power grid is important when it comes to location of PHES as there are losses and costs associated with power transmission distance. This being said to maintain minimal losses the PHES should be adjacent to medium voltage power lines.

### 4.2.7 Proximity to Roads

This factor is also in the covered in the location aspect of PHES. It mainly is a problem when considering the distance from which the new site is located from the existing access roads, as the construction of a new road to the potential site is high cost. The preferred location of a new PHES site would be adjacent to existing road infrastructure.

### 4.2.8 Distance/ Flow

This factor is related to the energy production of the new site. In PHES the distance and flow should be maximized for optimal energy production. This criterion corresponds with the length of penstock and head height of the system.

### 4.2.9 Environmental

Environmental aspects are important when thinking about an optimal location for PHES, not only because the very point of such a system is to decrease adverse environmental impacts that typical energy production systems provide, but also to avoid building on any environmentally unfit. Land. Such as areas protected by the law or considered to be inadequate for construction.

### 4.2.10 Urbanism

Like environmental this criterion is significant when constructing the new energy storage system. This factor is location based, the ideal area for a new OHES. Site is in a location where the area is more open then urban with no possibility if existing structures to be in the way.

## 4.3 Analytic Hierarchy Process

Analytic Hierarchy Process was developed by Thomas L. Saatay in the 1970s to aid in complex decision making. This process uses both mathematics and psychology to solve the problem, therefore eliminating the probability of human error by allowing for decision makers to one solution that suits the problem best. The process consists of 3 parts, first identifying the ultimate goal identifying all alternatives, and finally analyzing criteria used to find the conclusion.

The criteria are ranked on a scale from 1 to 9, explained further in Figure 4.1. These values are then transferred into a matrix and with a simple calculation (Equation 1) a pairwise comparison is conducted. In this work, 10 criteria were chosen as essential to the decision-making process of optimizing the location of Pumped Hydro-Electric Energy in the Lesser Poland and Pomeranian regions, See Table 4.3 for iteration 1 showing Pairwise Comparison of all attributes. The values determined in Table. 4.3 are then used to calculate the Normalized Pair-wise Matrix using Equation 2, next the Criteria Weight representing the relative importance of the chosen Criteria is calculated using Equation 3. Finally, to understand whether the calculated values meet the set standards, a Consistency Index and Consistency Coefficient is calculated using Equations 4 through 6. The Consistency Coefficient must be calculated to meet the global standards set below, in this work the CR must align with the 3$^{rd}$ option as our matrix is greater than 4x4.

- $CR \leq 5\%$, for 3x3 matrix
- $CR \leq 8\%$, for 4x4 matrix
- $CR \leq 10\%$, for the others matrix

**Table 4.1** Scale of criteria comparisons.

| Importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Both criteria are equally preferred |
| 3 | Moderate importance | One criterion slightly more preferred |
| 5 | Strong importance | One criterion strongly more preferred |
| 7 | Very strong importance | One criterion very strongly more preferred |
| 9 | Extreme importance | One criterion extremely more preferred |
| 2, 4, 6, 8 | Intermediate values | Intermediate grades for comparisons between the above |

*Source: Compiled from [25] and [26].*

**Table 4.2** The random index

| No. Criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0,58 | 0,9 | 1,12 | 1,24 | 1,32 | 1,41 | 1,45 | 1,49 | 1,51 | 1,54 |

*Source: Compiled from [25] and [26].*

**Table 4.3** Pair-wise Comparison Based on Rankings identified in Table 4.1 (Iteration 1)

| Criteria | | 1 Capacity | 2 Difference in Level | 3 Slope | 4 Length of Penstock | 5 Reservior Grouping | 6 Distance from Power Lines | 7 Distance to Road | 8 Distance / Flow | 9 Enviro. Impact | 10 Urbanism |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Capacity | 1 | 1 | 1 | 4 | 4 | 9 | 9 | 7 | 4 | 3 |
| 2 | Difference in Level | 1 | 1 | 1 | 4 | 4 | 7 | 7 | 5 | 4 | 1 |
| 3 | Slope | 1 | 1 | 1 | 3 | 4 | 5 | 5 | 3 | 1 | 1 |
| 4 | Length of Penstock | 0.25 | 0.25 | 0.33 | 1 | 1 | 5 | 5 | 3 | 0.33 | 0.33 |
| 5 | Reservior Grouping | 0.33 | 0.33 | 0.33 | 1 | 1 | 3 | 3 | 3 | 0.33 | 0.33 |
| 6 | Distance from Power Lines | 0.11 | 0.14 | 0.2 | 0.2 | 0.33 | 1 | 1 | 0.33 | 0.2 | 0.2 |
| 7 | Distance to Road | 0.11 | 0.14 | 0.2 | 0.2 | 0.33 | 1 | 1 | 0.33 | 0.2 | 0.2 |
| 8 | Distance / Flow | 0.14 | 0.2 | 0.33 | 0.33 | 0.33 | 3 | 3 | 1 | 0.33 | 0.33 |
| 9 | Environmental Impact | 0.25 | 0.25 | 1 | 3 | 3 | 5 | 5 | 3 | 1 | 1 |
| 10 | Urbanism | 0.33 | 1 | 1 | 3 | 3 | 5 | 5 | 3 | 1 | 1 |
| | Sum | 4.52 | 5.31 | 6.39 | 19.73 | 20.99 | 44 | 44 | 28.66 | 12.39 | 8.39 |

*Source: own elaboration.*

**Table 4.4** Normalized Pair-wise Matrix (Iteration 2)

| Criteria | | 1<br>Capacity | 2<br>Difference in Level | 3<br>Slope | 4<br>Length of Penstock | 5<br>Reservior Grouping | 6<br>Distance from Power Lines | 7<br>Distance to Road | 8<br>Distance / Flow | 9<br>Enviro. Impact | 10<br>Urbanism |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Capacity | 0.229 | 0.189 | 0.144 | 0.260 | 0.237 | 0.184 | 0.162 | 0.273 | 0.434 | 0.373 |
| 2 | Difference in Level | 0.229 | 0.189 | 0.144 | 0.260 | 0.237 | 0.143 | 0.126 | 0.195 | 0.434 | 0.124 |
| 3 | Slope | 0.229 | 0.189 | 0.144 | 0.195 | 0.237 | 0.102 | 0.090 | 0.117 | 0.109 | 0.124 |
| 4 | Length of Penstock | 0.057 | 0.047 | 0.048 | 0.065 | 0.059 | 0.102 | 0.090 | 0.117 | 0.036 | 0.041 |
| 5 | Reservior Grouping | 0.076 | 0.063 | 0.048 | 0.065 | 0.059 | 0.061 | 0.054 | 0.117 | 0.036 | 0.041 |
| 6 | Distance from Power Lines | 0.025 | 0.027 | 0.029 | 0.013 | 0.020 | 0.020 | 0.018 | 0.013 | 0.022 | 0.025 |
| 7 | Distance to Road | 0.025 | 0.027 | 0.029 | 0.013 | 0.020 | 0.020 | 0.018 | 0.013 | 0.022 | 0.025 |
| 8 | Distance / Flow | 0.032 | 0.038 | 0.048 | 0.021 | 0.020 | 0.061 | 0.054 | 0.039 | 0.036 | 0.041 |
| 9 | Environmental Impact | 0.057 | 0.047 | 0.144 | 0.195 | 0.178 | 0.102 | 0.090 | 0.117 | 0.109 | 0.124 |
| 10 | Urbanism | 0.076 | 0.189 | 0.144 | 0.195 | 0.178 | 0.102 | 0.090 | 0.117 | 0.109 | 0.124 |

*Source: own elaboration*

Table 4.5 and. 4.6 below present the results based on above outlined requirements and equations.

**Table 4.5** Criteria Weight Values

| Criteria | Criteria Weight | Rank |
|---|---|---|
| Capacity | 22.93 % | 1 |
| Head | 18.94% | 2 |
| Slope | 14.41% | 3 |
| Length | 6.50% | 6 |
| Reservoir Grouping | 5.92% | 7 |
| Proximity to Power Line | 2.05% | 9 |
| Road | 1.80% | 10 |
| Distance | 3.90% | 8 |
| Environmental Impact | 10.86% | 5 |
| Urbanism | 12.45% | 4 |

*Source: own elaboration*

**Table 4.6** Consistency Coefficient

| | |
|---|---|
| $\lambda_{max}$ | 10.65 |
| CI | 0.073 |
| CR | 4.88% |
| $CR \leq 10\%$ | |

*Source: own elaboration*

## 4.4 Criteria Classification

After conducting the AHP outlined in section 4.3, the top ranked criteria were taken and a further examined in QGIS. Due to the number of chosen attributes and size of the GIS analysis the criteria being, Capacity, Slope, and Urbanism were deemed the most essential and further examined. Importing the Corine Land Cover (CLC) map from , each topographical aspect has its own unique code and color with which it is associated, refer to Appendix I for codes and descriptions.

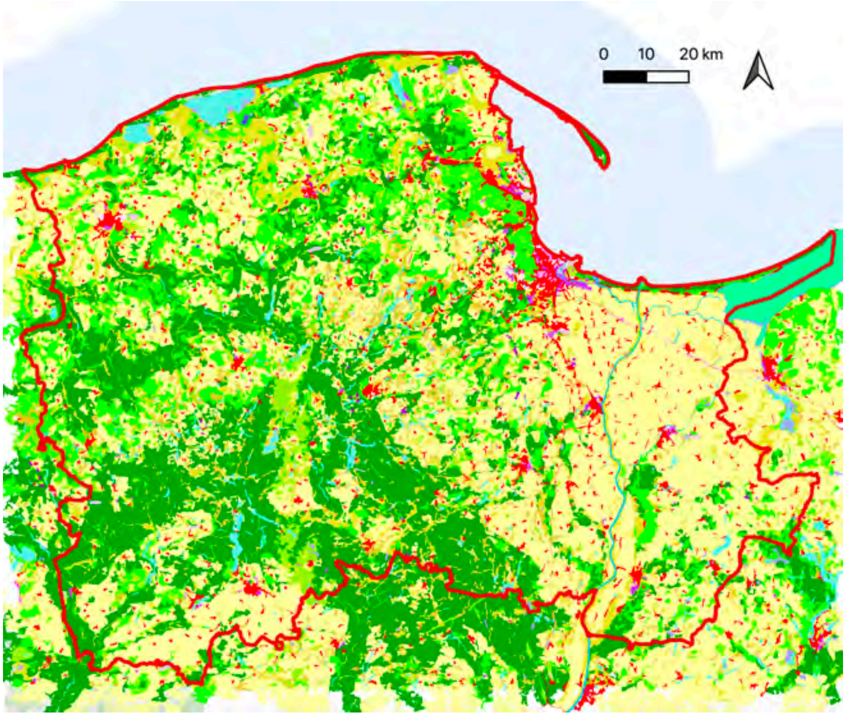


**Figure. 4.4** Corine Land Cover Map of Pomeranian Region.
*Source: own elaboration*

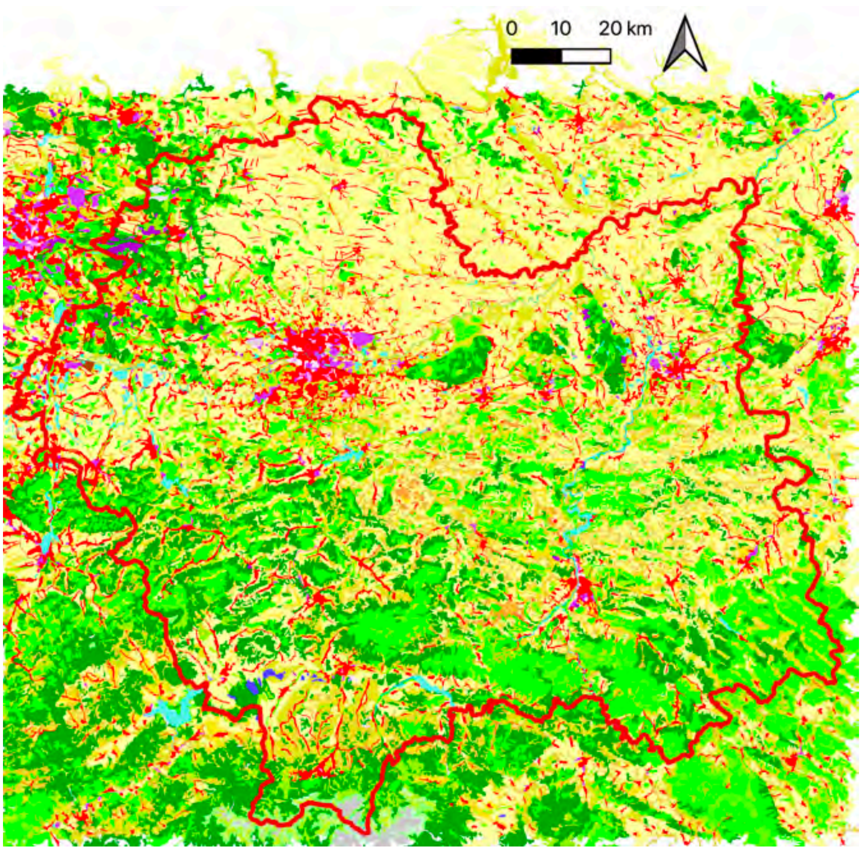


**Figure. 4.5** Corine Land Cover Map of Lesser Poland Region.
*Source: own elaboration*

Based on further examination of each topographical property in the Corine Land Cover Map, the following were filtered out: Code_18 : 512 – Water Bodies, 243 – Land principally occupied by agriculture with significant areas of natural vegetation, 313 – mixed forest , 321 – natural grasslands, and 323 – Sclerophyllous Vegetation. Although there are many options for construction of a new upper reservoir, in this work areas listed above are ideal locations. See Figures 4.6 and 4.7 that show the filtered existing Water Bodies that will serve as the lower reservoir and preliminary suitable areas for construction of upper reservoirs. This iteration shows suitable areas that are primarily based on the Corine land cover code descriptions. They will be further filtered in the following figures.

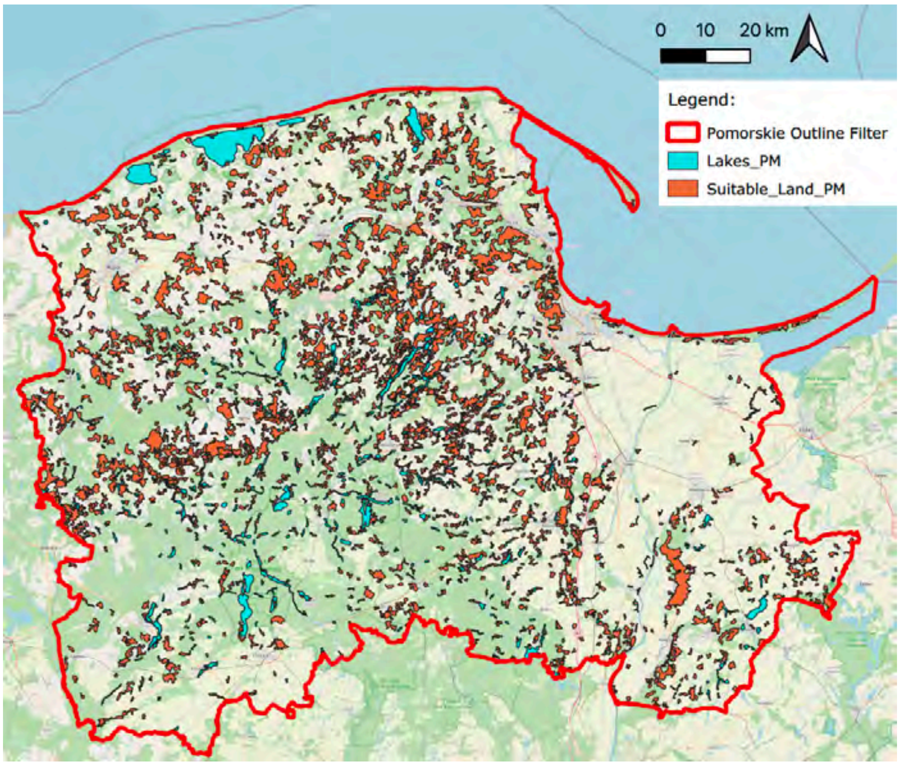


**Figure. 4.6** Map Showing Water Bodies and Suitable Area for Reservoir Construction (Iteration 1) in Pomeranian Region.

*Source: own elaboration*

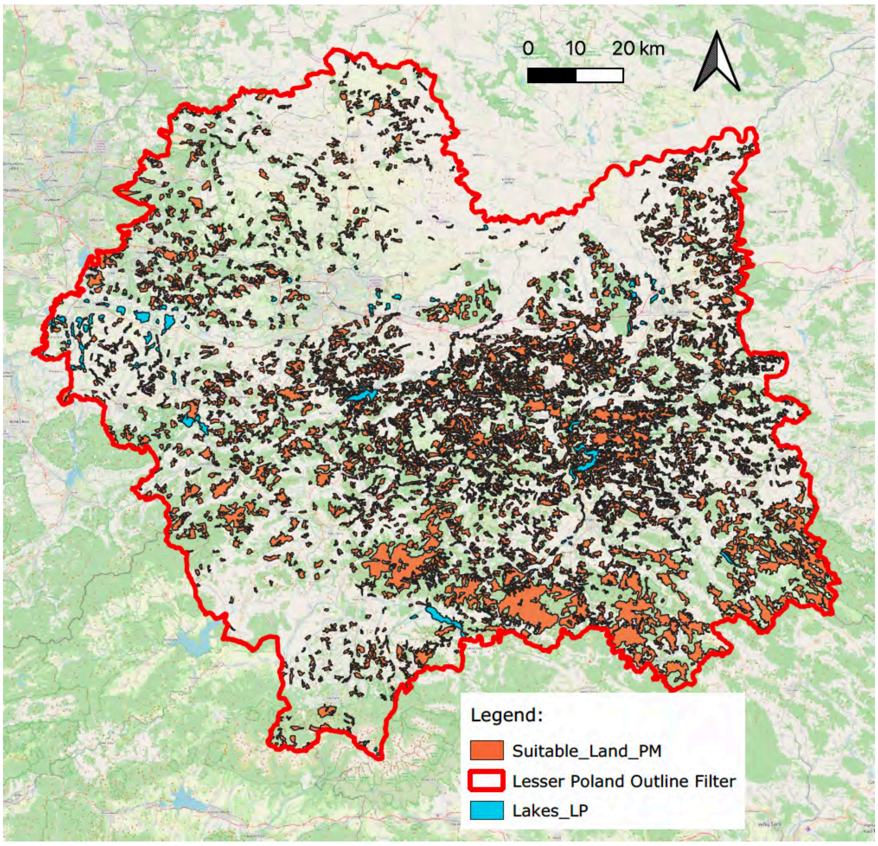


**Figure. 4.7** Map Showing Water Bodies and Suitable Area for Reservoir Construction (Iteration 1) in Lesser Poland Region.

*Source: own elaboration*

Next, to find the slope between the potential new location of the PHES site and the existing lakes the extracted areas are further examined. Using the 'zonal statistics' tool in the processing toolbox of QGIS. This is an algorithm that calculated certain statistics of the raster layer for each feature of an overlapping polygon vector layer. In the case of this thesis the mean, median and sum were calculated using this tool. Along with area of all the necessary areas can be found and logged in the 'attribute table' within each layer. Once this is complete and area of 1.5 km around the filtered water bodies is buffered out using the 'Buffer tool" in QGIS, this distance was determined based on extensive research and expert opinions. The Suitable area is then clipped to eliminate all areas that fall outside the buffered zone, this iteration of the suitable land will eliminate the areas that are too far from the existing bodies of water and are not realistic in the model.

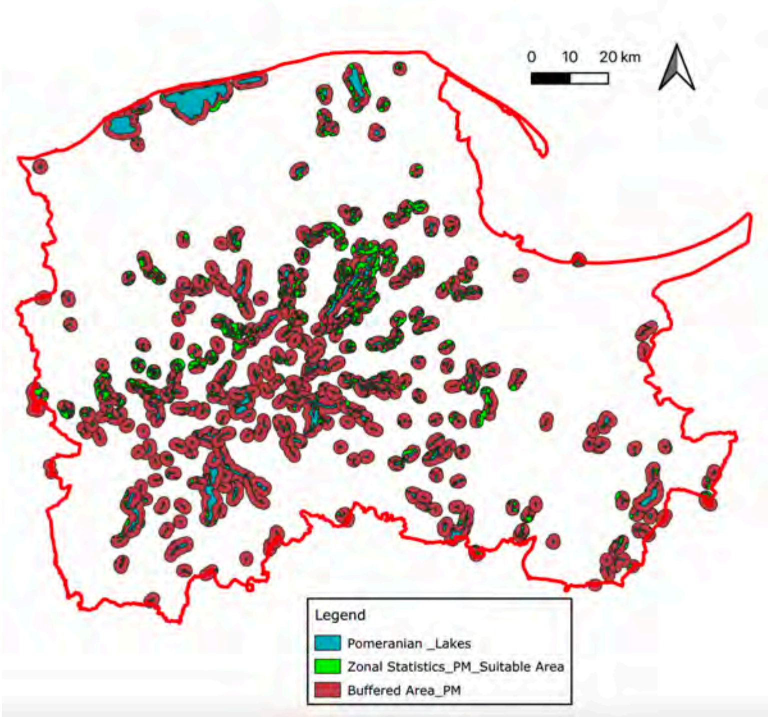


**Figure. 4.8** Map Showing Buffered Water Bodies and Sui table Area for Reservoir Construction (Iteration 2) in Pomeranian Region.

*Source: own elaboration*

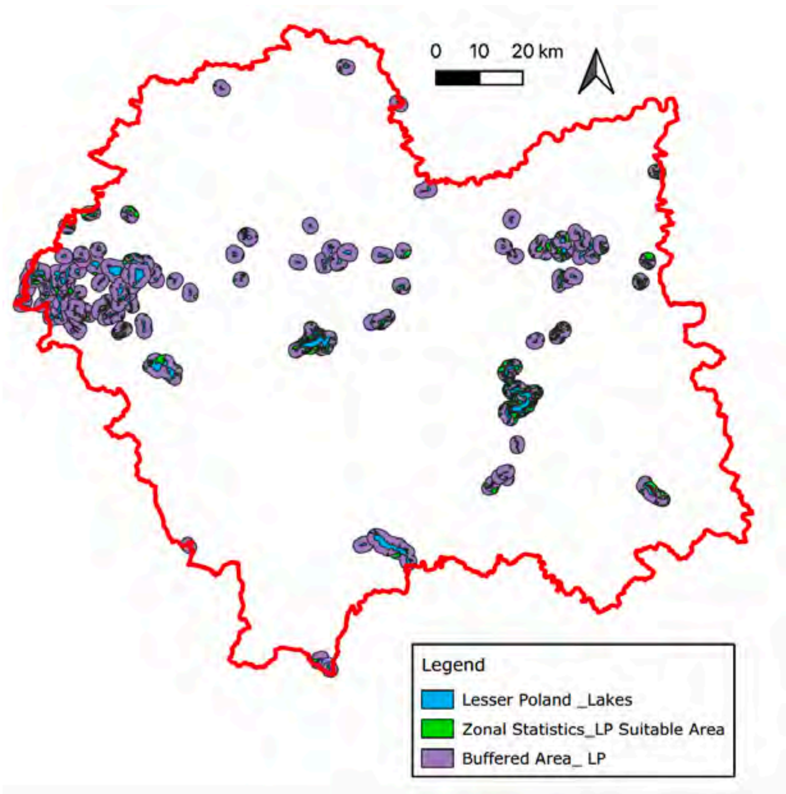


**Figure. 4.9** Map Showing Buffered Water Bodies and Suitable Area for Reservoir Construction (Iteration 2) in Lesser Poland Region.

*Source: own elaboration*

The height difference between the suitable land and bodies of water can be found by using the tool 'Join attributes by location'; this tool is defined as an algorithm that "..takes an input vector layer and created a new vector layer that is an extended version of the input one, with additional attributes in its attribute table"[27]. This combines the gathered information about height from both the suitable area buffered and the average height of the existing reservoir. Once this information is consolidated in one attribute for each voivodship, the average heights are subtracted using a simple equation in the field calculator. Based on research the larger height difference or head the better, as the Power output will be maximized.

First, all the areas with a height difference equal to or greater than 50 were filtered. For the Pomeranian Region 62 areas remained and for the Lesser Poland Region 61 suitable areas remained. See figures 4.10 and 4.11 for results.

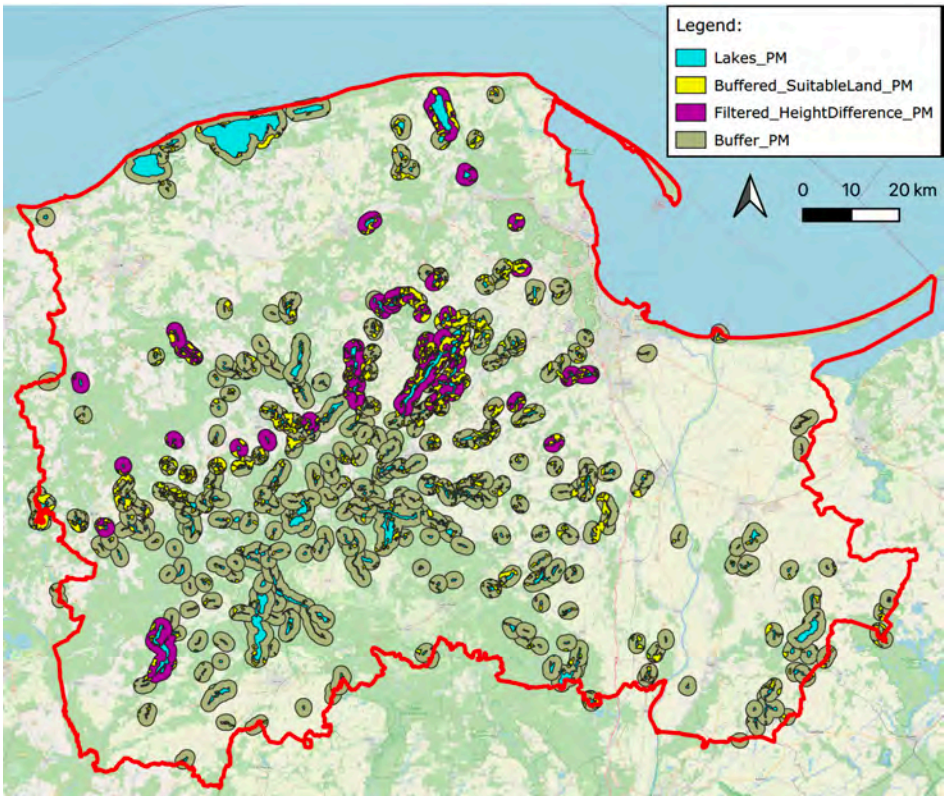


**Figure. 4.10** Map Showing Locations filtered by Height Difference between Reservoirs in Pomeranian Region.

*Source: own elaboration*

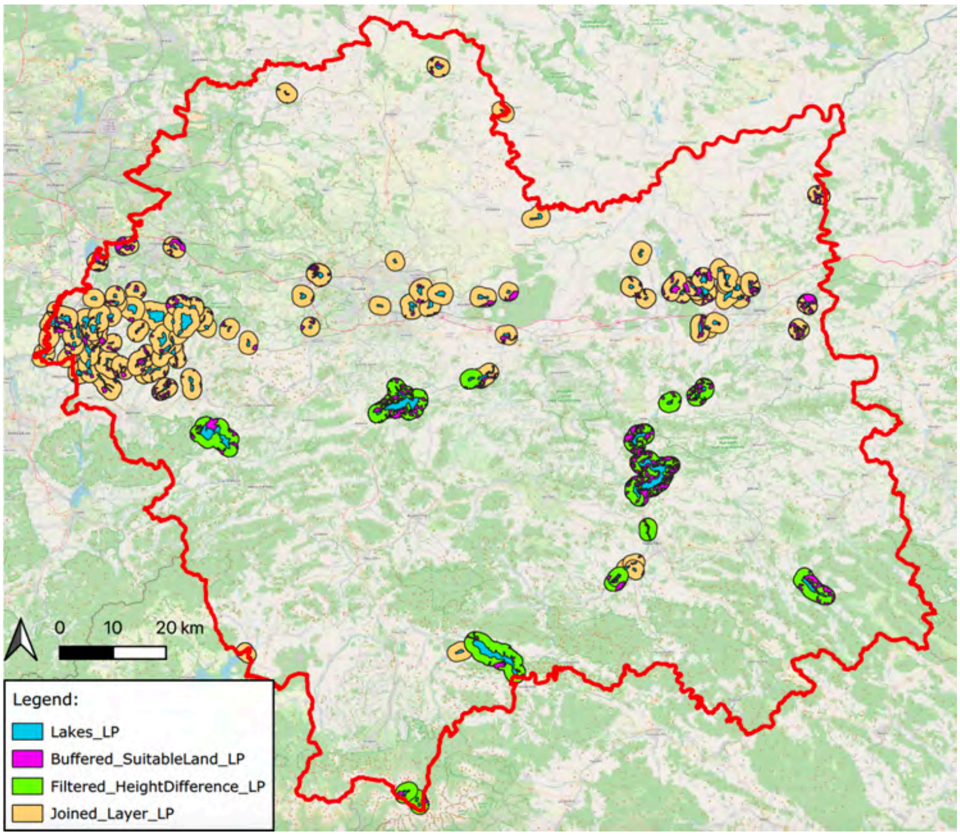


**Figure. 4.11** Map Showing Locations filtered by Height Difference between Reservoirs in Sites in Lesser Poland Region.

*Source: own elaboration*

To further eliminate un-suitable land the area of suitable land is filtered using the assumption that the area of the reservoir site must be greater than or equal to 50,000 $m^2$ and the area of the existing reservoir must be at least double this size at 100,000 $m^2$. All these assumptions are made based on extensive literature review and research of expert opinions for characteristics of PHES sites.

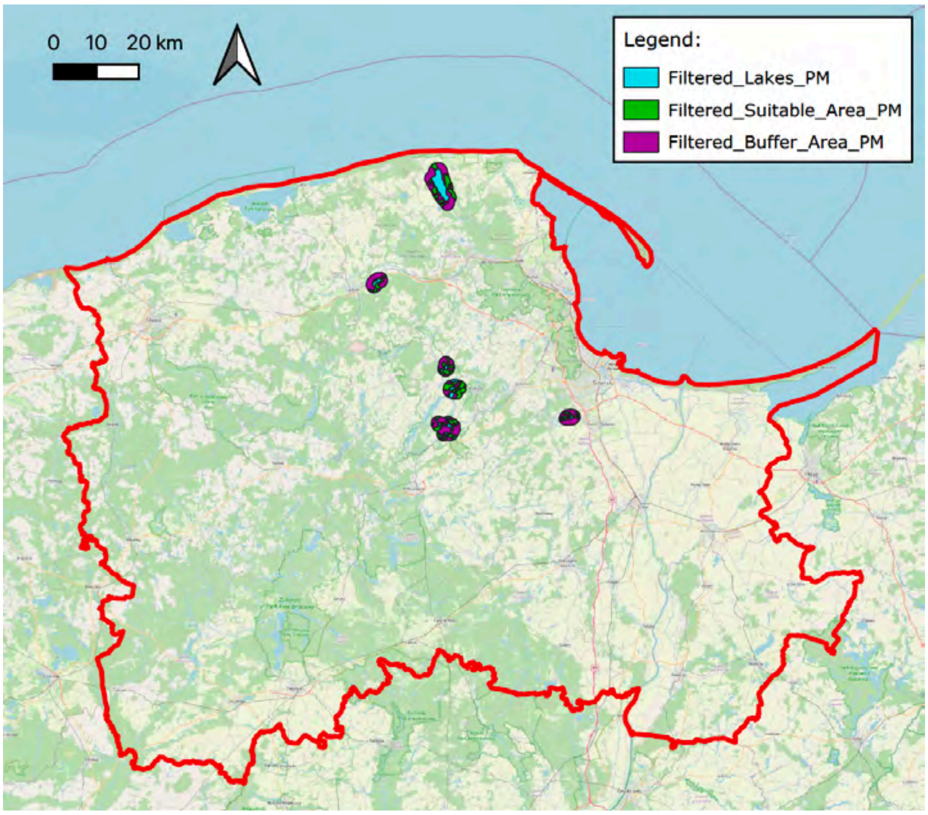


**Figure. 4.12** Map Showing Ideal locations for PHES Sites in Pomeranian Region.
*Source: own elaboration*

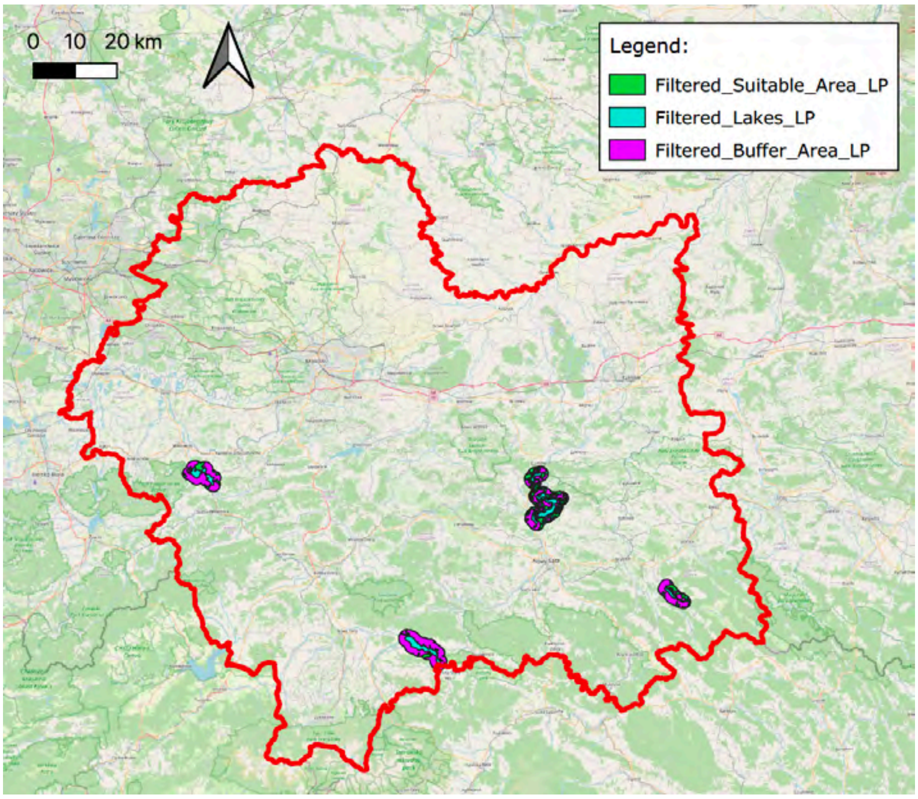


**Figure. 4.13** Map Showing Ideal locations for PHES Sites in Lesser Poland Region.
*Source: own elaboration*

From the results gathered the top ten results that met all. Outlines criteria are presented.

Finally, to understand the theoretical potential of the proposed sites, a Power calculation is rendered using Equation 1 below. Based on the topographical criteria of head height and acceptable size based on suitable area each of these potential sites, the power output can be represented by Figure X.X below.

$$P = V \times H \times \rho \times g \times \eta \quad \text{(Equation 1)}$$

Where: P is the Power output of the Pumped Hydro-Electric Plant over time (MWh), $V$ is the Volume of the Upper Reservoir ($m^3$), $H$ is the Head Height between the existing lower and proposed upper reservoirs (m), $\rho$ is fluid density of water (1000 kg/$m^3$), $g$ is acceleration due to gravity (9.81 m/$s^2$), and $\eta$ is efficiency of the output (95%).

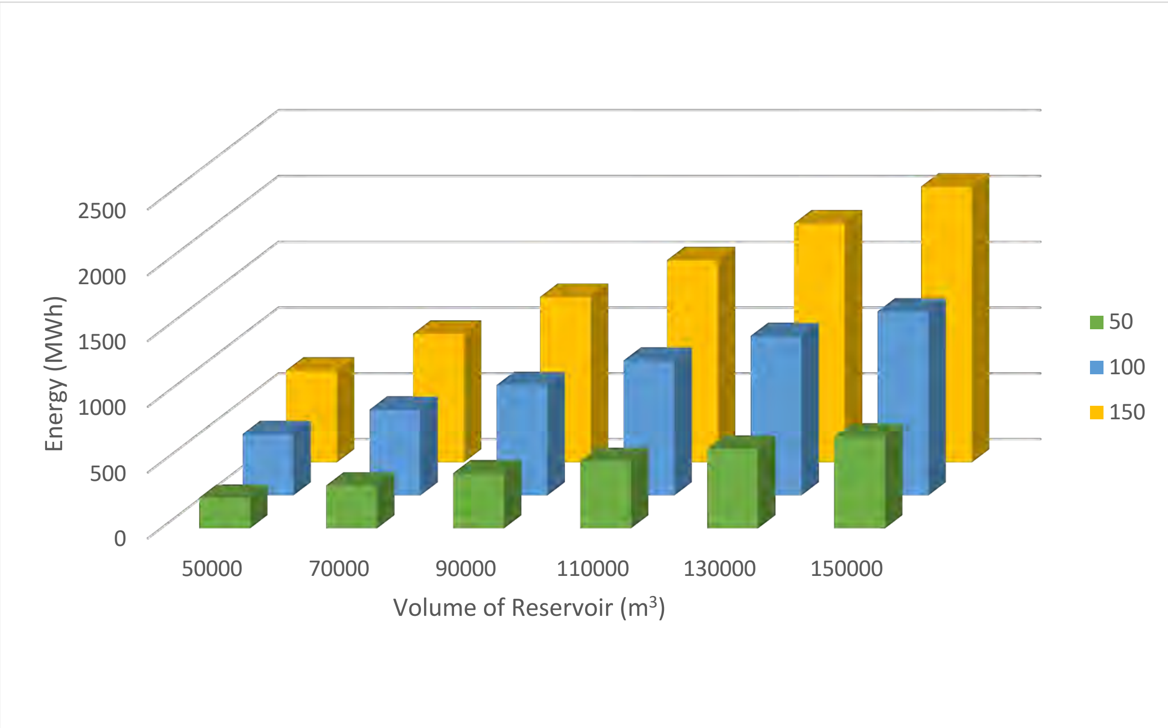


**Figure. 4.14** Energy (MWh) output of the. Potential Sites based on Volume and Head.
*Source: own elaboration*

To simplify the process 3 different volumes of reservoirs are assumed ranging from 50,000 $m^3$ to 150,000 $m^3$. Since the installation of a new upper reservoir involves excavation of land, installation of floor and retaining walls etc.

a head height range between 50 m and 150 m was analyzed and presented. Lastly, in order to maintain consistency, the volume of each site was calculated based on a reservoir depth of 10 m.

To justify the analysis of the chosen reservoirs as outlined above the potential Power must be calculated based on the height difference between the existing lower and new proposed upper reservoir. Using a simple Power Equation to ensure legitimate locations are chosen. For the sake of this project eight locations were proposed that met the exigencies out lined, four in Lesser Poland and four in the Pomeranian regions. Equation 1 inputs change based on head, flow and efficiency. This equation was used to eliminate unsuitable locations of PHES in the areas examined.

# 5. Results

The aim of this paper was to explore the capabilities of installing new Pumped Hydroelectric Storage in both Pomeranian and Lesser Poland voivodships of Poland, using AHP and QGIS to substantiate ideal locations. After the initial analysis presented above, the criterion examined was chosen by the ranking established with the AHP method and the top criteria was taken and further examined in GIS, a geographic database used to analyze and visualize the data in the form of maps presented in chapter 4. This information was then taken and analyzed in MS Excel to present the final locations and corresponding potential Energy output possible at each site, shown in the following subsections.

## 5.1. New PHES Locations

The results of this work are mainly demonstrated using the GIS-geographic database with support of criteria ranking from Analytical Hierarchy Process. The maps obtained are based off height difference, area of existing lower reservoir and area of land deemed as suitable to support the construction of a reservoir following the characteristics previously outlined. The final results show that the most optimal locations in the Pomeranian Region are located around Klodno Lake, Radunskie Lake, and Gowidlinskie Lake as shown in Figures below; Whereas the most optimal locations in Lesser Poland are located around Mucharskie Lake and Roznowskie Lake.

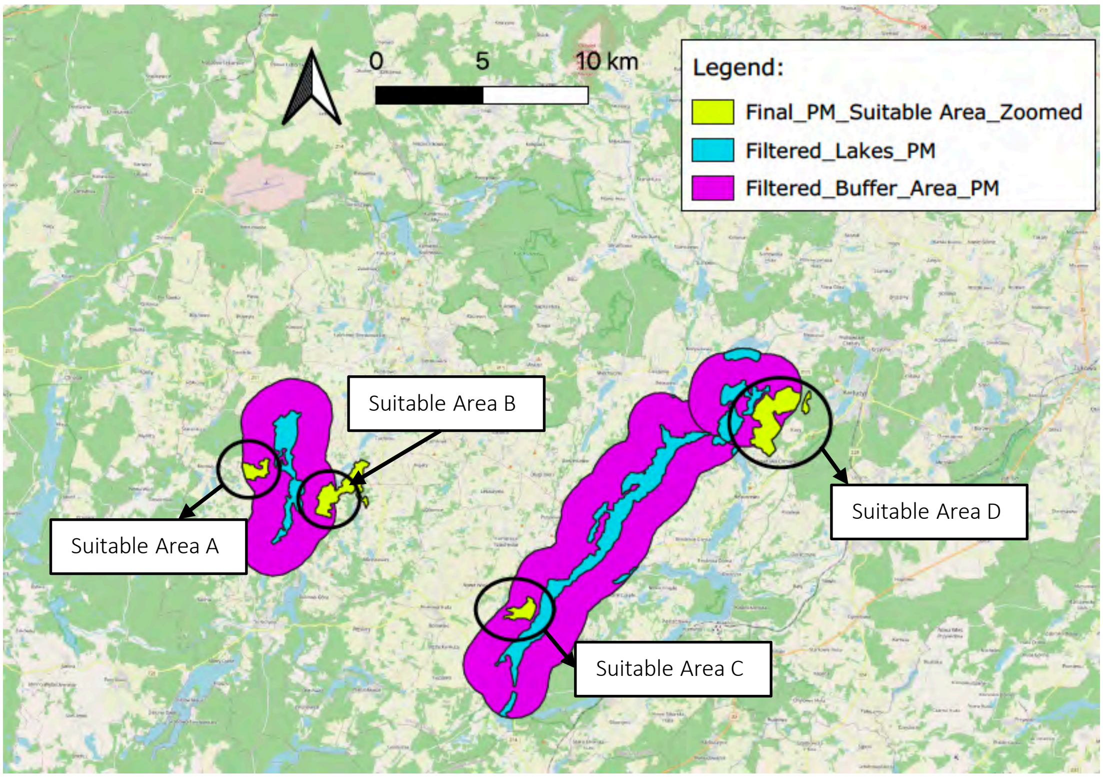


**Figure 5.1** Zoomed PHES Site Potential Location Map of Pomeranian Voivodship. *Source: own elaboration*

The areas regarded as suitable in this study are shown in Figures 5.1 and 5.2 in yellow and using equation 1 above, the information regarding the area and assumed theoretically appropriate head heights were used to calculate the Energy Rating at each site, see Tables 5.1 and 5.2 In order to forego any discrepancies that may be present at each site; for the Pomeranian Region at 'Suitable Area A' and 'C' 60% of the area available is used as truly usable land for construction of a new upper reservoir. While at 'Suitable Area B' and 'D' only 20% of the land was used for the calculation to regulate and maintain a realistic size for a new upper reservoir. Also, for the Lesser Poland Region, 'Suitable Area A', 'B' and 'C' only 20% of the land was used again due to control the size of the reservoir, while 60% of 'Suitable area C' was calculated.

**Table 5.1** New PHES Suitable areas and Energy Rating in Pomeranian Region.

| | Suitable Area A | Suitable Area B | Suitable Area C | Suitable Area D |
|---|---|---|---|---|
| Area Available | 830,000 $m^2$ | 2,460,000 $m^2$ | 870,000 $m^2$ | 4,510,000 $m^2$ |
| Area of Upper Reservoir | about 498,000 $m^2$ | about 492,000 $m^2$ | about 522,000 $m^2$ | about 902,000 $m^2$ |
| Theoretical Energy Rating based on Head Height | 79 TJ @ 50 m | 78 TJ @ 50 m | 82 TJ @ 50 m | 143 TJ @ 50 m |
| | 158 TJ @ 100 m | 156 TJ @ 100 m | 165 TJ @ 100 m | 286 TJ @ 100 m |
| | 250 TJ @ 150 m | 247 TJ @ 150 m | 262 TJ @ 150 m | 453 TJ @ 150 m |

*Source: own elaboration*

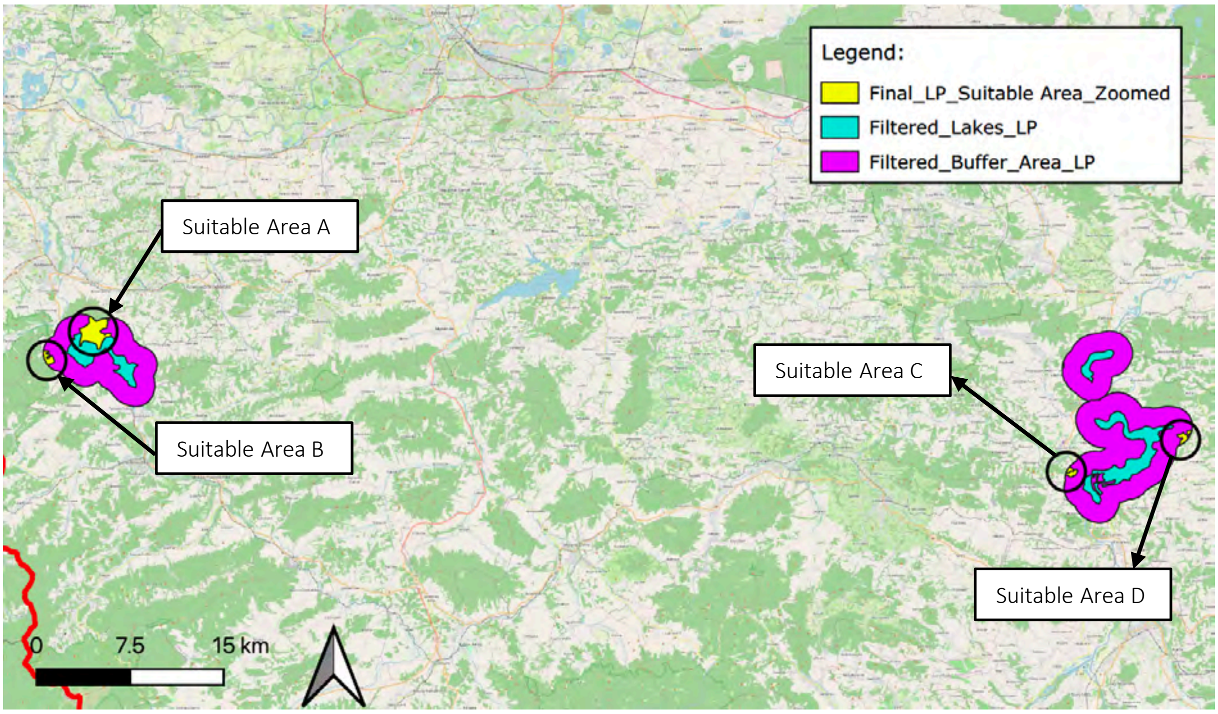


**Figure 5.2.** Zoomed PHES Site Potential Location Map of Lesser Poland Voivodship.
*Source: own elaboration*

**Table 5.2** New PHES Suitable areas and Energy Rating in Lesser Poland Region.

| | Suitable Area A | Suitable Area B | Suitable Area C | Suitable Area D |
|---|---|---|---|---|
| Area Available | 6,920,000 $m^2$ | 1,350,000 $m^2$ | 1,290,000 $m^2$ | 590,000 $m^2$ |
| Area of Upper Reservoir | about 1,384,000 $m^2$ | about 270,000 $m^2$ | about 258,000 $m^2$ | about 354,000 $m^2$ |
| Theoretical Energy Rating based on Head Height | 219 TJ @ 50 m | 42 TJ @ 50 m | 41 TJ @ 50 m | 56 TJ @ 50 m |
| | 439 TJ @ 100 m | 85 TJ @ 100 m | 82 TJ @ 100 m | 112 TJ @ 100 m |
| | 695 TJ @ 150 m | 135 TJ @ 100 m | 129 TJ @ 150 m | 178 TJ @ 150 m |

*Source: own elaboration*

Based on this data calculated it is concluded that that as hypothesized there is a high theoretical potential for new PHES installations in Pomeranian and Lesser Poland Regions.

## 5.2. Existing PHES Locations

To corroborate the findings attained in this paper, existing PHES sites were located in both Pomeranian and Lesser Poland regions, see figure 5.3 below. Zarnowiec Power Plant located in Zarnowieckie Lake in the Pomeranian region. This PHES Plant consists of two lakes, Zarnowieckie Lake a naturally occurring body of water and Czymanowo Lake, a man-made lake. The capacity of this system is 716 MW, which is attained from an upper reservoir that is 0.94 $km^2$ and a penstock length of 1.15 km, see figure 5.3 below for area. Inversely in the south of Poland in the Lesser Poland Region, Porabka-Zar Power Plant uses Miedzybrodzie Bialskie reservoir as the lower reservoir- dammed, and the upper man-made lake Miedzybrodzie Bialksie. This PHES Power Plant was built in 1979 and has an installed capacity of 540 MW which is accomplished by a lake area of 0.14 $km^2$ and penstock or tunnel length of 1.27 km. As can be seen in the progression of the GIS extracted maps, the data proves that while existing sites are feasible, existing sites such as Zarnowiec were also selected in the model.

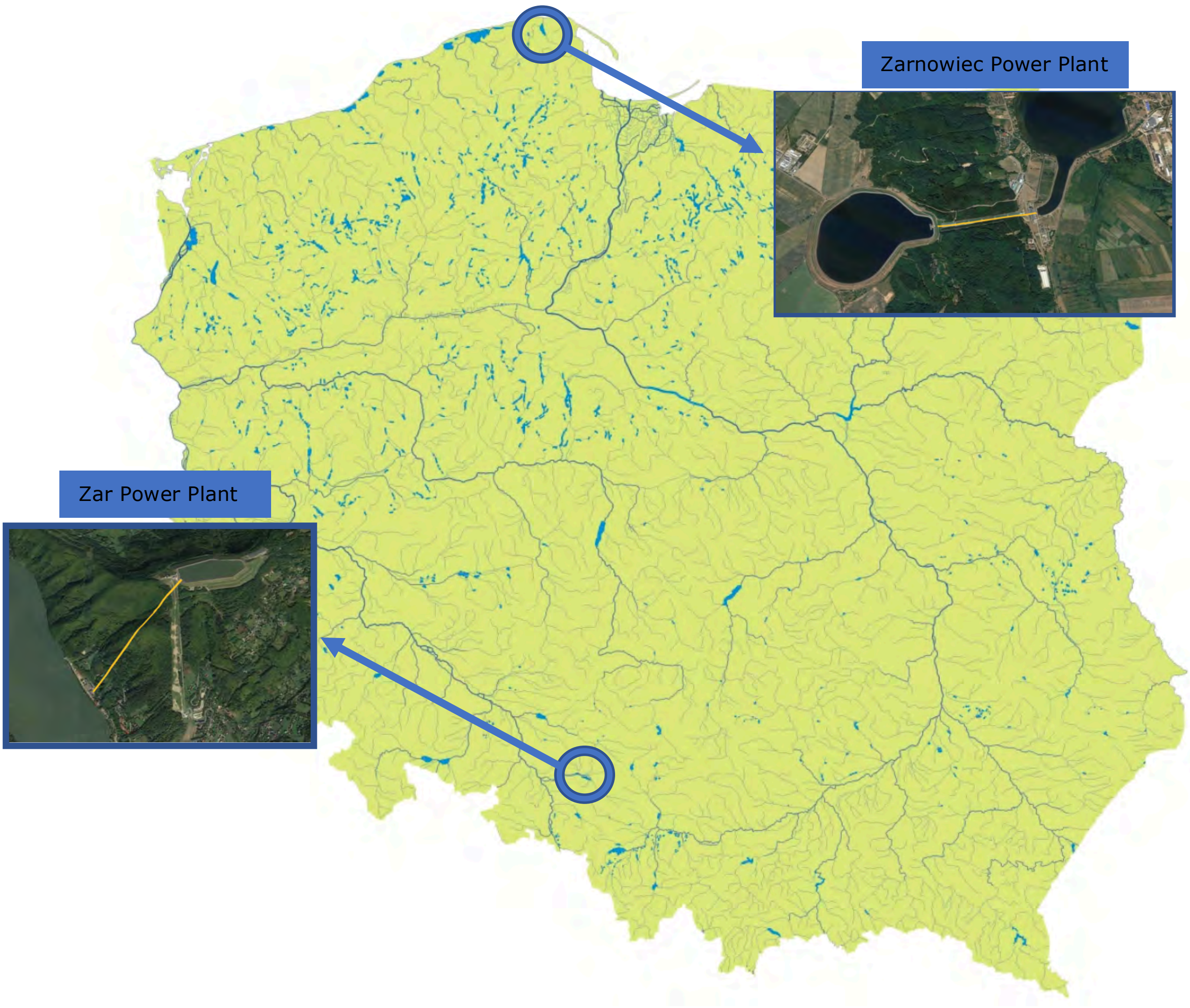


**Figure. 5.3** Existing PHES in Poland.
*Source: own elaboration.*

## 5.3. Future Work

Due to the magnitude of data available for both Pomeranian and Lesser Poland regions of Poland, many assumptions were made to restrict the results to a scale appropriate for the scope of this work. Furthermore, although a thorough literature review was conducted the data examined was based on certain conjecture as a complete geological survey was not conducted of the new proposed areas to confirm their compatibility with the construction of a new upper reservoir and all associated devices and appurtenances. Based on the results gathered, the four new proposed locations in both Pomeranian and Lesser Poland regions were extracted from the GIS model based on all factors and criteria outlined throughout this work, along with the shape of the suitable land that possessed a footprint that was square or rounded, opposed to elongated and mis-shaped to ensure the theoretical site was in fact practical for the construction of a new PHES site.

For future work, enhancements of the model should include the following developments. First, incorporating a more thorough investigation of the geological status of the presented optimal locations as this will identify the type and suitability of the soil. This is often done by bore holes prior to construction to ensure the soil has structural capabilities. Also, a further survey of existing conditions and suitable land. In this work locations were chosen from the Corine Land Cover Map; While this is sufficient to eliminate areas that are unsuitable due to obvious reasons, land that was deemed suitable may have flaws associated such as existing or ongoing construction, owned by third parties, and various other reasons. Nevertheless, the optimal locations collected would benefit from a careful field study. Lastly, in this work the head heights of 50m, 100, and 150m are simulated in this model to present optimal results for the locations. Although this model isolated areas with the largest difference in height the exact height should be further determined when considering construction of the upper reservoir. In that during the construction process, land is leveled and filled as required and this will play a major role in the exact head height and therefore Power output.

# 6. Conclusions

As the usage of fossil fuel heavy energy sources becomes more restrictive due to environmental and economical reasons, the evolution and expansion of renewable based energy storage systems has become a primary focus to meet the increasing demands facing the energy grid. The installation of large-scale energy storage systems such as Pumped Hydro-Electric Storage systems allows for renewable energy sources to take the lead in energy supply. Sources such as Solar Collectors and Wind energy which are known for their fluctuations and instability diminish these discrepancies by storing their energy in a long term or short-term time period in PHES. Maintaining these large-scale systems will continue to lead Poland in the direction of Net Zero emissions. The installation of these storage systems is essential in stabilizing the electricity grid, and it can be concluded based on research that PHES are the largest electrical energy Storage systems in the world. The aim of this study was to show the methodology associated with selecting an optimal location for the installation of a new Pumped Hydro Electric system in both Pomeranian and Lesser Poland Provinces. In order to develop a model that shows the ideal location AHP and QGIS were used together to determine and filter the criterion to match the selected categories. While many different aspects can be considered applicable to the installation of PHES, a thorough literature review and articles allowed for suitable criteria to be prioritized. The criteria were ranked using the AHP and the top locational and environmental criterion were further examined in the Geographical Information System to extract any unsuitable land and bodies of water. As the topographical approach used was to maintain a existing body of water as the lower reservoir while constructing a new upper reservoir, the suitable land surrounding existing bodies of water was extracted. While there were many options for suitable land this work excludes all areas that are protected by law and areas that were deemed unfit to provide an ideal site for PHES. Using QGIS the information was buffered, extracted, and filtered all unsuitable areas and created maps showing this process. These maps can be used and further examined in the attributes tables get the final height differences and areas of land/ existing water bodies a power calculation was run to understand what theoretical potential the proposed sited possess. The results obtained throughout this process present that these regions are capable of storing a high-power capacity that will be fundamental to stabilizing the electrical energy grid and therefore exponentially reduce the number fossil fuels currently being used to maintain the grid.

These results show that that using this type of geographical and analytical algorithm is practicable.

# 7. References

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# Appendix 1


*Source:[28]*