AMERICAN UNIVERSITY OF BEIRUT

ASSESSMENT OF TECHNO-FINANCIAL FEASIBILITY OF SEAWATER PUMPED STORAGE IN LEBANON

by
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ABSTRACT
OF THE THESIS OF

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Title: Assessment of Techno-Financial Feasibility of Seawater Pumped Storage in Lebanon

As renewable energy sources penetrate Lebanon's power sector, there is an increasing need for new energy storage systems to diversify and improve the national grid. Pump hydroelectric storage is an energy storage technology that has the potential to improve the stability of the power grid by deploying intermittent renewable energy sources and enabling load leveling strategies. Seawater pump storage (SPS) is a promising pump hydroelectric storage technology that uses the sea as a lower reservoir. As Lebanon, which suffers from constant stress on its freshwater resources, is located along the Mediterranean Sea, SPS is a viable energy storage option for improving the national grid.

This thesis assesses the technical and financial feasibility of using SPS in Lebanon. The Geographic Information System (GIS) software was used to locate potential sites for the artificial upper reservoir of an SPS plant along the Lebanese coastline. The GIS model output indicates the presence of two suitable sites, located in Ras Chekaa, North Lebanon Governorate. Each site's suitability was further studied in terms of environmental, social, land ownership, geotechnical, and water table vulnerability aspects, which were then used to narrow down the options to one feasible site. The feasible site possesses an elevation head of 173.71 m and a power capacity of 36.3 MW, which is 40% of the 93 MW average difference in electricity demand during peak hours in Lebanon. The proposed SPS plant built on this site will help in peak load leveling by operating daily, for the five peak hours between 5 pm and 10 pm.

The proposed SPS plant initial investment cost is estimated at $117.06 million, while the annual operation and maintenance costs are estimated at $2.27 million. To assess the financial feasibility of the plant, revenues were estimated under three different scenarios of electricity price sold from the plant (0.13, 0.16, and 0.21 $/kWh) and under three different discount factor values (3.5%, 7%, 12%) for the expected 40 years lifespan of the plant. The results indicate that the project will make economic sense if the price of electricity sold is at least 0.16 $/kWh while adopting a discount factor of 3.5% or lower, or if the price of electricity sold is at least 0.21 $/kWh while adopting a discount factor of 7% or lower.

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ABBREVIATIONS

EDL: Electricité du Liban

EPDC: Electrical Power Development Co., Ltd.

GIS: Geographic Information System

IRENA: International Renewable Energy Agency

LCEC: Lebanese Center for Energy Conservation

MEI: Melbourne Energy Institute

MEW: Ministry of Energy and Water

MITI: The Ministry of International Trade and Industry of Japan

MW: Megawatt

MWh: Megawatt Hour

NDC: Nationally Determined Contribution

NREAP: National Renewable Energy Action Plan

PHES: Pumped hydroelectric energy storage

SPS: Seawater Pumped Storage

CHAPTER I

INTRODUCTION

A. Motivation and objective of the study

The objective of this study is to assess the techno-financial feasibility and explore potential sites to build seawater pumped storage (SPS) plants near the Lebanese coastline. The implementation of a SPS system helps reduce the problem of peak load demand. Moreover, the national targets to increase the portion of renewable energy sources in the Lebanese energy mix imposes the need for energy storage systems to ensure grid stability and reliability. The Lebanese coastal area extends over 225 km along the Mediterranean Sea. It is characterized by a narrow coastal plain that is 6.5 km at its widest point lying below the Lebanese Mountains. According to the topographic elevation map of Lebanon, the elevation of areas near the coastline can reach 268 meters. Thus, the presence of elevated areas on the coastline provides a base ground to proceed in assessing the application of SPS in Lebanon. Given that Lebanon's water resources are under stress, assessing the use of seawater instead of freshwater as a storage medium is important in order to reduce the pressure on freshwater resources.

B. The situation of the Lebanese power sector

The Lebanese power sector lacks the security of power supply due to its critical production capacity deficit. As a consequence, Lebanese citizens rely on diesel generators to overcome frequent daily power cuts. This electric instability is progressive with time due to a perpetual increase in demand and continuous decay of the existing power plants. This problem traces back to the Lebanese civil war between 1975 and

1990, where the electricity sector infrastructure was damaged and degraded. As a consequence, the major rehabilitation plan, “Power Sector Master Plan”, was launched in 1992-2002, but it failed due to the continued imbalance of supply and demand.

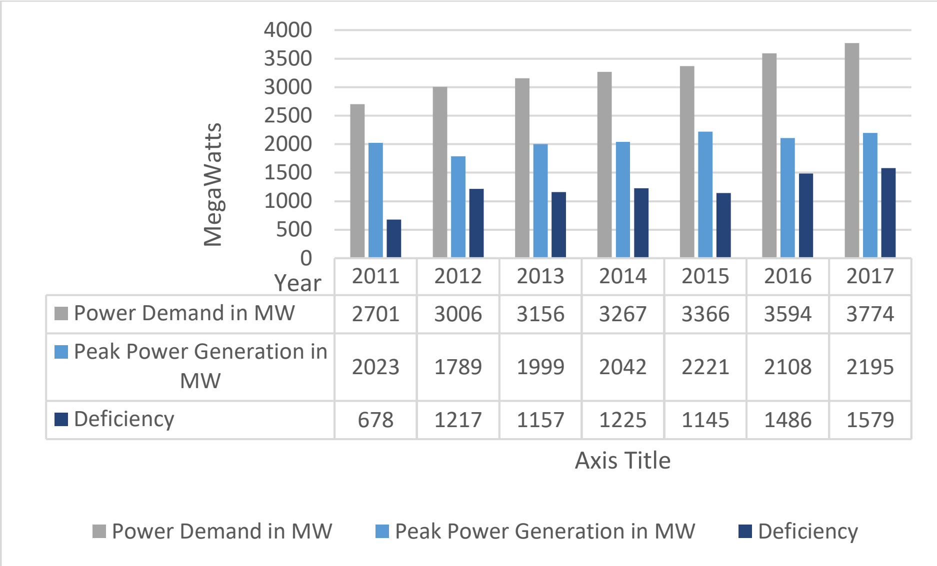
In Lebanon, the electrical energy is generated from thermal and hydroelectric power plants. Thermal energy production represents the primary source of electricity production and the hydropower plants energy production constitutes only a maximum of 4.5% of the total power generated (CDR, 2018). And since Lebanon doesn’t produce oil and gas, most of the energy needs are imported. This leaves the country’s economy vulnerable to the volatility of oil prices.

EDL, Electricité du Liban, monopolizes the Lebanese electricity sector. It is a public institution under the Ministry of Energy and Water (MEW) responsible for the generation, transmission, and distribution of electrical energy. Among other participants in the electricity sector are the hydroelectric power plants owned by the public company “Litani River Authority”, concessions for hydroelectric power plants owned by the private companies “Ibrahim and Al Bared” that sell their electrical production to EDL. Moreover, electricity is purchased from barges or imported through regional interconnections. According to the World Bank report “Distributed power generation for Lebanon” in 2018, the capacity of EDL plants was 1884 MW, of purchased barges was 388 MW, and of purchased imported was 240 MW, which results in total generation capacity of 2512 MW (ESMAP, 2020). Table 1 represents the capacity and performance of the existing EDL power plant, barges and power imports as of 2018.

Table 1: The capacities and performance of the existing EDL power plant, barges and power imports (MEW, 2019).

Facility	Fuel type	Installed capacity (MW)	Effective capacity 2018 (MW)	Total generation cost (c$/kwh)
Existing EDL 2018				
Zouk 1 Thermal Power Plant	HFO	607	440	14.75
Jieh 1 Thermal Power Plant	HFO	343	180	19.39
Zouk 2 ICE Power Plant	HFO/NG-Z	198	157	10.83
Jieh 2 ICE Power Plant	HFO/NG-J	78	63	11.19
Zahran I CCPP	DO/NG-ZAH	469	420	13.62
Deir Ammar I CCP	DO/NG-DA	464	430	14.96
Baalbek Open Cycle GT	DO	64	57	20.26
Tyr Open Cycle GT	DO	72	56	21.44
Richmaya-Safa Hydro	-	13	3	3.66
Naameh (Landfill Gas)	-	7	7	1.00
Existing barges				
Power Barge Zouk	HFO/NG-Z	187	195	13.95
Power Barge Jiyeh	HFO/NG-J	187	195	14.03
Existing IPPs				
Litani Hydro	-	199	47	3.97
Nahr Ibrahim Hydro	-	32	17	2.65
Bared Hydro	-	17	6	2.65
Kadisha Hydro	-	21	15	2.65
Hrayche Thermal Power Plant	HFO	35	46	20.13
Power imports				
Imports from Syria and Egypt		276	69	15.35

According to the MEW, in 2017, the demand for electrical energy reached approximately an annual average of 2604 MW that is equivalent to 3774 MW of peak power demand using a load factor of 69% (CDR, 2018). The electricity produced and purchased in 2017 reached an annual average of 1611 MW, equivalent to an annual peak of 2335 MW of power. As a result, the energy gap in 2017 between the peak demand and peak supply reached 1579 MW which constitutes 38% of the peak demand. Figure 1 shows the energy deficiency between the values of peak power demand and peak power generation for 2011 until 2017.



Year	2011	2012	2013	2014	2015	2016	2017
Power Demand in MW	2701	3006	3156	3267	3366	3594	3774
Peak Power Generation in MW	2023	1789	1999	2042	2221	2108	2195
Deficiency	678	1217	1157	1225	1145	1486	1579

Figure 1: Peak power demand, power generation and Deficiency (MEW, 2019).

1. Electrical load curves

The daily load curve is a graphical representation of load variation in MW with the 24 hours of the day on the power station. According to EDL, the graph in Figure 2 represents the summer (June) and the winter (January) load curves for 2015. Since EDL has not been able to satisfy national electricity demand alone its electrical supply load curves can't reflect the real electricity demand. Therefore, the country's demand curves are used to analyze the variation of load during the day and between the two seasons. Referring to the load curves illustrated in Figure 2, the maximum peak demand occurs in the evening during both the summer and winter seasons. This can be attributed to residential activity demand. Moreover, in both seasons, the demand starts decreasing after the evening maximum peak demand until it reaches a minimum demand at around 4 am. In the summer (June), during the day the peak demand is related to commercial activities and air condition during office hours as it can be indicated by the decrease in demand load at 5 pm approximately. For the summer, the evening peak demand load occurs at 9 pm which is linked to lighting and air conditioning, mostly in the residential sector. In the winter (January), the evening peak demand starts at 5 pm and reaches a maximum demand at around 7 pm due to lighting and heating. The peak to off-peak electrical demand ratio is approximately 164% for winter (January) and 146% for summer (June) (EDL, 2015).

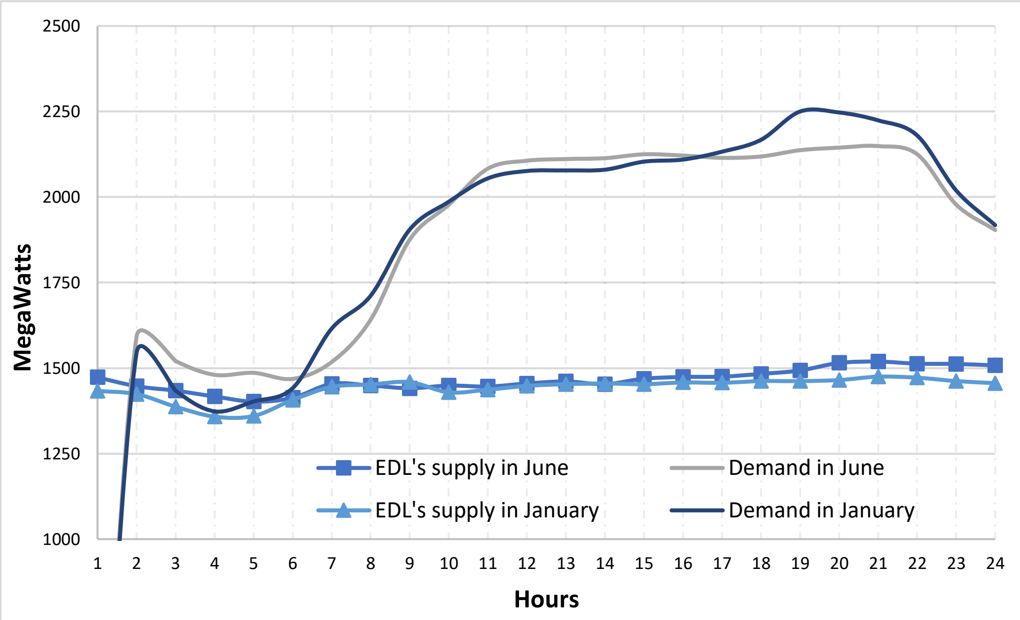


Figure 2: Demand and Supply Load Curves for January and June 2015 (EDL, 2015).

According to Figure 3, which represents the electricity daily demand curve for each month of the year 2015, the electricity demand is the highest during August, July, and February, respectively. Moreover, the peak demand value occurs during February (2326 MW) followed by a peak value during August (2320 MW) as highlighted in Figure 3.

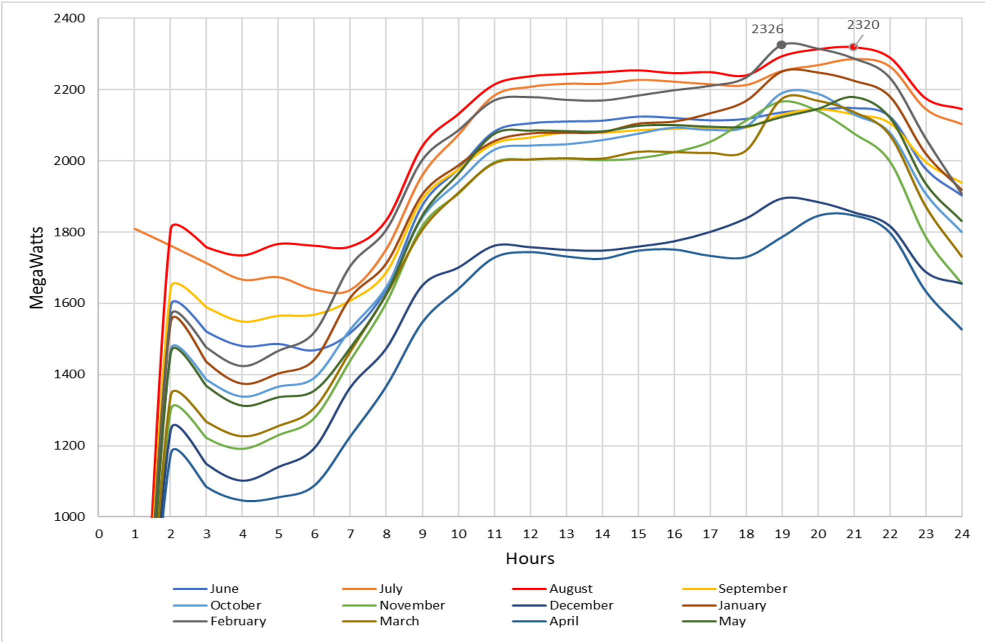


Figure 3: Electricity daily demand curve for each month of 2015 (EDL, 2015).

Referring to Figure 3, the peak electricity demand hours are between hour 17 and 22. Figure 4 represents the difference in electricity demand during peak hours for each month of the year 2015. The average value of the difference in electricity demand during peak hours is 93 MW.

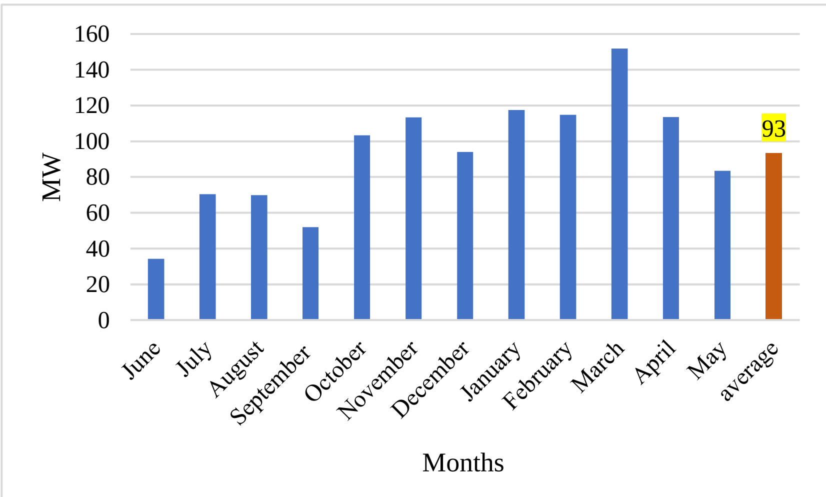


Figure 4: The difference in electricity demand during the peak hours for each month of the year 2015 (EDL, 2015).

2. Renewable energy sector in Lebanon

Exploring renewable energies in Lebanon helps to enhance the country's electricity system, decrease the dependency of the electricity sector on fossil fuels, and reduce environmental impacts.

The first form of renewable energy in Lebanon was the Bécharé hydroelectric power plant built under the French mandate in 1924. This plant is still operational today but partially. The period between the 1920s and the 1970s witnessed the implementation of multiple hydroelectric power plants. At that time, hydropower constituted 75% of total electricity production in Lebanon (IRENA, 2020). After the end of the Lebanese civil war in 1990, the introduction of renewable energies to the power sector reemerged, especially the use of solar water heaters in residential activities. However, traditional power plants were built between 1990 and 1998 to satisfy the increase in electricity demand.

a. Renewable energy targets and policy framework

The latest electricity reform paper adopted by the Lebanese government in 2019 incorporated a renewable energy target of 30% by 2030. The Prime Minister announced this target in 2018 (IRENA, 2020). Before 2018, the government of Lebanon has been active in defining targets to improve renewable energy capacity through the National Renewable Energy Action Plan (NREAP). The NREAP document was initiated in 2015 by LCEC and MEW and it presented the proposed goals and actions to meet the government target of 12% of total primary energy consumed, electricity and heating, by 2020 (LCEC, 2016).

In March 2019, Lebanon endorsed the Paris Agreement in Parliament under Law 115. Thus, the renewable energy commitments are included in Lebanon's Nationally

Determined Contribution (NDC) to the Paris Agreement. Where NDC aims for a 20% total share of renewable energy sources for power and heating demand of which 15% consists of unconditional targets and 5% consists of conditional targets. And back in November 2006, Lebanon ratified the Kyoto protocol with Law No. 738 and pledged to reduce the country's greenhouse gas emissions by decreasing the energy demand and increasing the energy supplied by renewable sources to 12% by 2020.

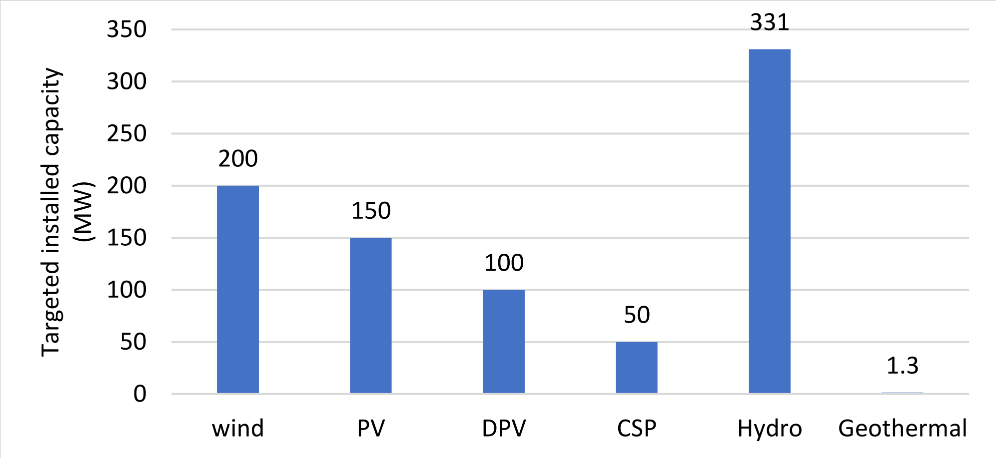


Figure 5: Renewable energy targeted installed capacities in the NREAP 2016–2020 (LCEC, 2016).

3. Lebanon renewable energy potential and status

a. <u>Hydropower</u>

Hydropower was the first renewable energy source deployed in Lebanon. Five hydroelectric plants are operating with a total installed capacity of 286 MW. However, the lack of proper maintenance for several of these plants caused a decrease in efficiency and production losses of around 30-40% (IRENA, 2020).

Four main sources consist of the main potential of hydropower, and they are listed as follow:

- Rehabilitation of existing power plants;

NREAP 2016-2020 projects that rehabilitation of existing hydroelectric plants can add more than 1000 GWh to their annual generation capacity.

- Construction of new power plants;

  The MEW, in collaboration with the consultant Sogreah-Artelia, has conducted a Master Plan Study to evaluate the hydroelectric potential along the main river streams in Lebanon. The study showed a potential of 368 MW in the peak scheme and 263 MW in the run-of-river scheme.

- Micro-hydro run-of-river applications and generation from non-river sources;

  A potential of 5 MW can be derived from the micro-hydro run-of-river applications and generation from non-river sources (CEDRO, 2013).

The hydroelectric targets set in the NREAP are 331.5 and 473 MW in 2020 and 2030, respectively, including the rehabilitation of existing plants. These targets and projects in the pipeline are summarized in Table 2.

Table 2:Hydroelectric NREAP targets and potential (IRENA, 2020).

	2020 target	**2030 target**	**Contracted capacity**	**Project in the pipeline**	**Potential**
Hydroelectricity	331.5 MW	473 MW	N. A	300 MW	Additional 382-487 MW

b. Onshore wind power

The National Wind Atlas, published in 2011, was the first evaluation of Lebanon’s wind energy potential. It estimated a potential of 6100 MW mean wind capacity (Hassan, 2011). However, according to LCEC, this potential should be decreased to 5400 MW taking into consideration the assumptions on installation density, minimum wind speed requirement, and maximum slope constraints. Moreover, a recent study by IRENA in 2019, conducted at 100m height, estimated a higher potential of 6233 MW of wind capacity and indicated that over 1 558 km2 of land in Lebanon is suitable for utility-scale wind farms (IRENA, 2020).

Auctions are the main policy instrument used for developing wind energy projects. The first round was launched in 2013 and as a result, a PPA contract was signed between the government of Lebanon and three private developers to implement the first 200-240 MW wind farm in the under-developed region of Akkar. This process has been followed by second-round auctions in April 2018 to develop additional wind projects with a capacity between 200 and 400 MW. However, the second auction received 42 offers from 74 companies increasing the capacity by a total of 4000 MW distributed among different regions in Lebanon as shown in Figure 6 (LCEC, 2016).

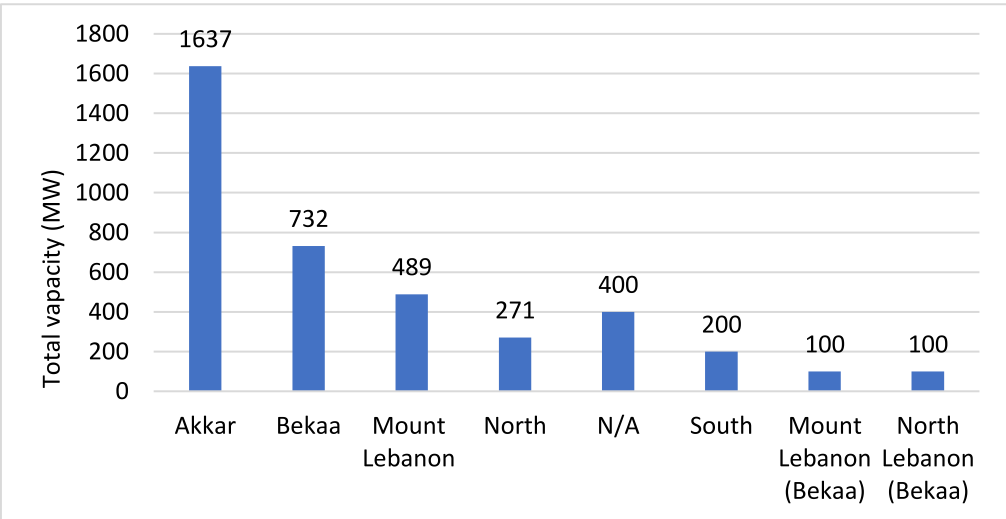


Figure 6: Total capacity per region in response to the second round of wind auctions (LCEC, 2016).

The wind targets set in NREAP are 200 MW and 450 MW in 2020 and 2030 respectively. Table 3 highlights these targets along with the contracted capacity and projects in the pipeline until 2019.

Table 3: Wind power potential and NREAP targets; contracted and planned projects as of 2019 (IRENA, 2020).

Wind	2020 target	2030 target	Contracted capacity	Project in the pipeline	Potential
	200 MW	450 MW	200-220 MW	500 MW	1500 MW

c. <u>Solar power</u>

The International Renewable Energy Agency (IRENA)'s Global Atlas for Renewable Energy, Figure 7, shows that the annual average solar irradiation in Lebanon varies between 1 520 kWh/m2/year and 2 148 kWh/m2/yea with most areas having a value over 1 900 kWh/m2/year. Based on this solar irradiation data, IRENA estimated a utility-scale solar PV potential of 182 615 MW and indicated that 5558 km2 of Lebanon's land is suitable for installing utility-scale solar PV (IRENA, 2020). A prior assessment was done by NREAP and estimated a solar PV capacity of 87 000 MW which is less than twice IRENA's estimate. However, the total installed solar PVcapacity from large-scale projects and distributed installations was only 56.7 MW at the end of 2018 (LCEC, 2016).

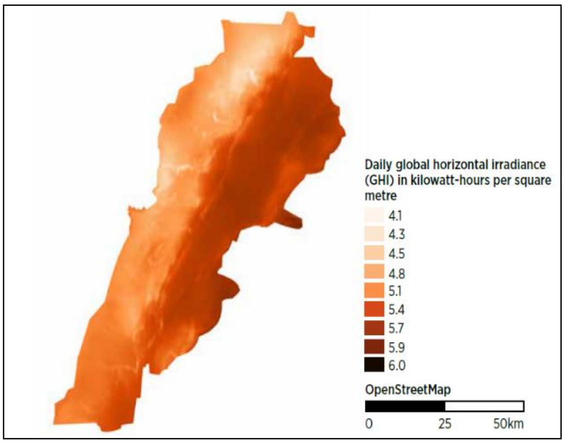


Figure 7: Solar resource potential: Annual average daily GHI (kWh/m2) (IRENA, 2020).

The first grid-connected large-scale solar PV project installed in Lebanon was the Beirut River Solar Snake. The project was initiated in 2013 by the MEW and aimed to install a PV farm of more than 1MWp on the Beirut river's bed. This project was successful and improved the efficiency of solar PV in Lebanon. The NREAP set national targets for large-scale PV of 150 MWp and 300 MWp in 2020 and 2030 respectively, as shown in the Table 4. To grow this energy source, the MEW is launching two separate bids for solar farms with a total production capacity of around 450 MW (MEW, 2018). The first auction was launched in 2017 to install 12 solar farms with a capacity between 10 and 15 MWp each. The second-round auction for installing 24 farms with a total capacity of 240-360 MWp is being prepared by MEW and LCEC and will be launched by the end of 2020 (IRENA, 2020).

According to NREAP, the distributed solar PV consists of a PV system that satisfies local demand for one or multiple consumers. The main installation of distributed PV is by the private sector benefiting from NREAP loans. Where the installation of distributed PV by this sector rose from 0.33 MWp in 2010 to 56.37 MWp in 2018 (IRENA, 2020). Moreover, to increase the installation of distributed PV systems the NREAP set a target for this technology of 100 MWp and 150 MWp in 2020 and 2030, respectively, as shown in Table 4.

Table 4: The large-scale PV and distributed PV NREAP targets and potentials (IRENA, 2020).

	2020 target	**2030 target**	**Contracted capacity**	**Project in the pipeline**	**Potential**
Large-scale PV	150 MWp	300 MWp	2 MWp	1030 MWp	87636 MWp
Distributed PV	100 MWp	150 MWp	56.37 MWp	1.2 MWp (public sector) 56 MWp (private sector)	N/A

CHAPTER II

PUMPED HYDROELECTRIC ENERGY STORAGE.

A. Energy storage systems

Energy storage technologies are in high demand nowadays. They play a key role in meeting global climate action and sustainable development goals set in the Paris agreement. These technologies help stabilize the power output of intermittent renewable energy sources such as wind and solar energy. Nonetheless, they are used to improve grid stability.

Different energy storage technologies exist. The mature ones include battery storage and pumped hydro storage. The ones in the initial state of technological development include flywheel, molten salt, and compressed air. For large grid size energy storage, the pumped storage technology is the best in terms of economy, reliability, and technical maturity.

B. Pumped hydroelectric storage

1. Principles

Pumped hydroelectric energy storage (PHES) stores potential energy in water pumped from a lower reservoir to a higher reservoir. During the off-peak time, electricity is used to power a pump to raise water and store it in the upper reservoir. In this mode, the electric energy is converted into potential energy stored in water. Then during the high electricity demand periods, the stored water is released back through the hydro turbines to produce electric power.

The typical design of PHES plant, as shown in Figure 8, consists of two reservoirs or lakes where water passes between the upper and lower reservoir through tunnels and shafts. The tunnel system is composed of a penstock followed by a powerhouse that contains pumps and hydro-turbines then a tailrace where water exits in the powerhouse. Also, valves are used to control the flow of water between the two reservoirs. The relatively low energy density of the PHES system can be encountered by either a large reservoir or a large height difference between reservoirs.

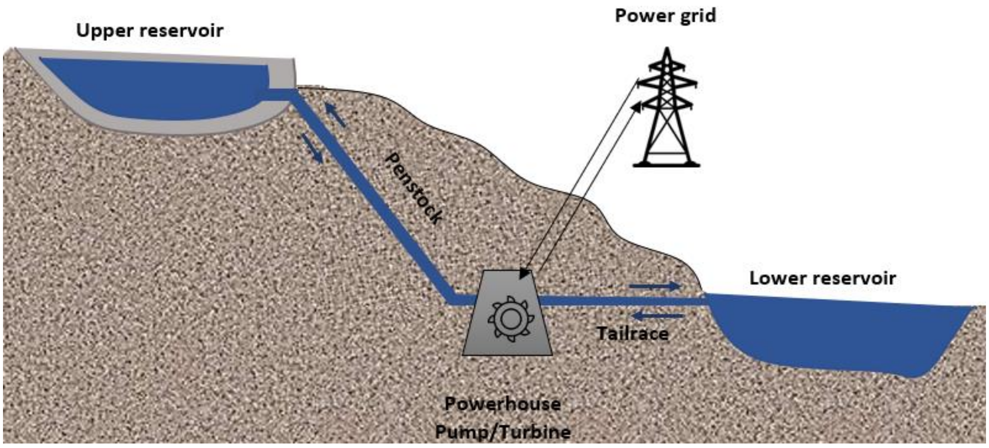


Figure 8: Schematic of a pumped storage hydropower plant.

In general, PHES is used to balance the electricity demand by allowing system operators to time-shift the power generated. Referring to Figure 9, the mechanism of pumping water to store it uphill at night, the period of low electricity demand, needs more electricity than the electricity produced by water flowing downhill during the day. However, this comes with the benefit of flattering the daily load curve by decreasing the range of energy supply needed as shown in Figure 10. This is achieved by shifting the electricity produced overnight to serve daytime loads. During the period of low electricity demand, the effective demand is increased by storing the excess energy supplied. On the other hand, and during the period of high electricity demand, the effective demand is decreased since the energy stored is used to produce electricity (EIA, 2013).

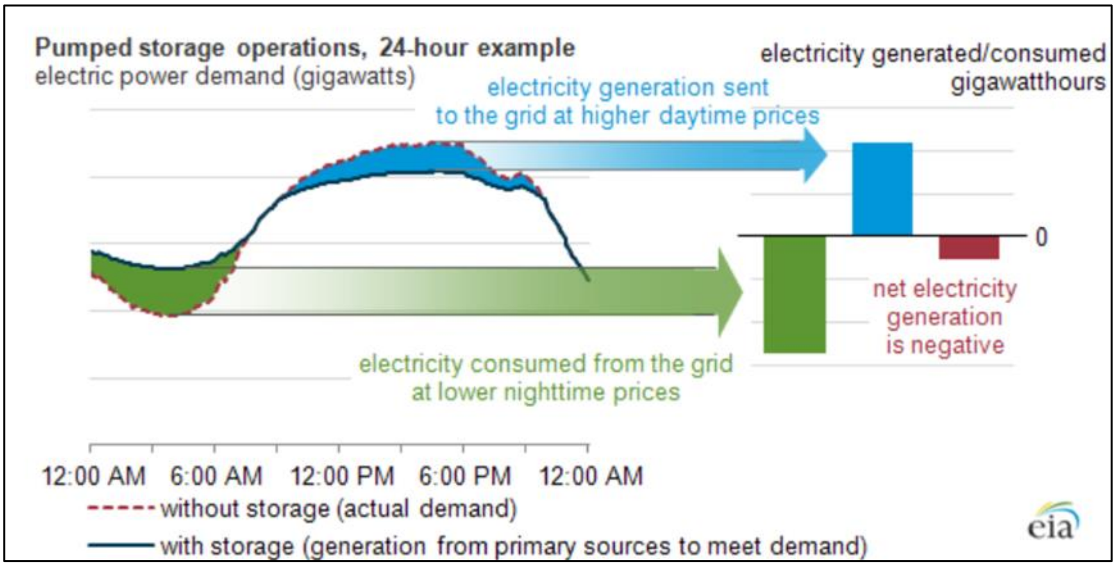


Figure 9: Role of PHS on Electricity Power Systems (EIA, 2013).

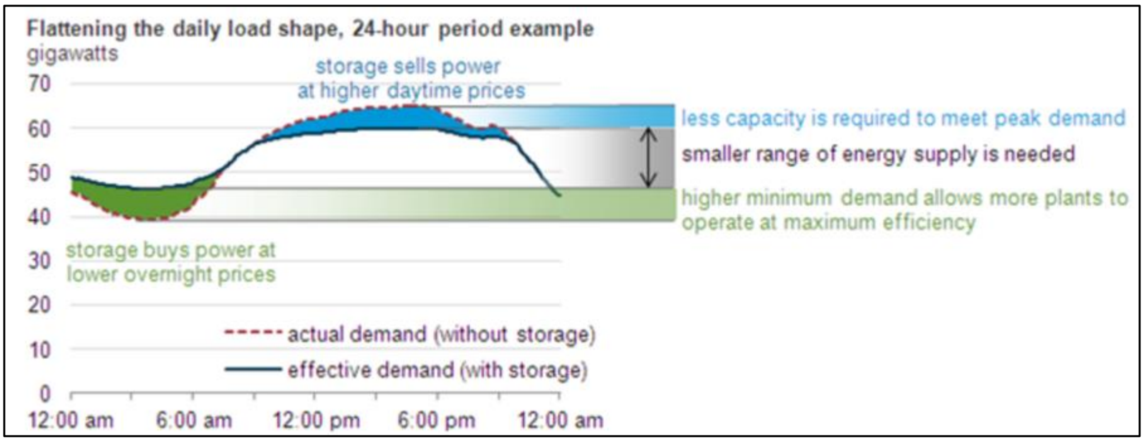


Figure 10: Flattening the Daily Load Shape (EIA, 2013).

Nowadays, PHES is used to stabilize the intermittent output of renewable energy resources such as wind and sun. The system’s fast reaction time makes it an ideal storage system to be integrated with renewable energy sources. Where PHES plant can reach full production capacity in 15 seconds and can have a reaction time of fewer than two minutes from complete shutdown to full power and less than five minutes from complete shutdown to full pumping capacity (Pérez-Díaz et al., 2014).

2. *Power and capacity calculations*

The power generated from the PHES plant is derived from the water flow rate at the turbine (Q) and the head difference between the upper and lower reservoir (H). The following formula is used to calculated using the power capacity (Connolly, 2010):

Equation 1:Power capacity in Watts

$$P = \eta \times \rho \times g \times Q \times H$$

Where:
P = Power Capacity (Watts)
ρ = Density of water (kg/m^3)
g = Acceleration due to gravity (9.81 m/s^2)
Q = Discharge at the turbine (m^3/s)
H = available "Net" head (m)
η = efficiency of the system (%)

Most pumped storage plants use a single unit pump-turbines, Francis or Deriaz turbines, which act as a pump and turbine. Independently on the type of turbine chosen, the PHES plants possess a rapid response to demand for power. The round-trip PHES energy efficiency, combining uphill and generating downhill, varies between 75%-80% (Zipparro & Hasen, 1993).

Table 5: Round-trip PHES energy efficiency (Zipparro & Hasen, 1993).

	Low %	High %
Generating Components		
Water conductors	97.40	98.50
Pump turbine	91.50	92.00
Generator motor	98.50	99.00
Transformer	99.50	99.70
Subtotal	**87.35**	**96.44**
Pumping components		
Water conductors	97.60	98.50
Pump turbine	91.60	92.50
Generator motor	98.70	99.00
Transformer	99.50	99.80
Subtotal	**87.80**	**90.02**
Operational	98.00	99.50
Total	**75.15**	**80.12**

The required energy storing capacity is dictated from the daily power production required, meaning the plant capacity multiplied by the needed plant operational time per day in hours. The formula of energy storage in MWh is dependent on the hydraulic head and the reservoir capacity. Thus, knowing the energy storing capacity MWh and the hydraulic head, the following formula can be used to obtain the required capacity of the upper reservoir in m3 (Connolly, 2010):

Equation 2: Energy storing capacity in MWh

$$SC = \frac{\rho \times g \times H \times V \times \eta T}{3.6 \times 10^9}$$

Where:
SC = Storage capacity (MWh)
V = Volume of water that is drained and filled each day (m^3)
ρ = Mass density of water (kg/m^3)
g = Acceleration due to gravity (m/s^2)
H = Effective head (m)
ηT = Efficiency of the Turbine

3. Global trends

By absorbing energy surplus and supplying it once needed, PHES is seen as a promising technology to increase the penetration of renewable energy in the power system. Since the 20th century, energy storage as PHES, water battery, has provided flexibility and stability to the power grid (IEA, 2018). Lately, PHES accounted for 94% of global energy storage capacity. By the end of 2018, the pumped storage capacity reached 160.3 GW. The top 10 countries and the rest of the world pumped storage capacity are represented in Figure 11. The increase in interest in PHES in several countries is due to the increase in penetration of renewable energy sources to the grid. China highly contributed to the recent increase in PHES where it added 15,000 MW of capacity since 2010 due to government targets for renewables (IHA, 2019).

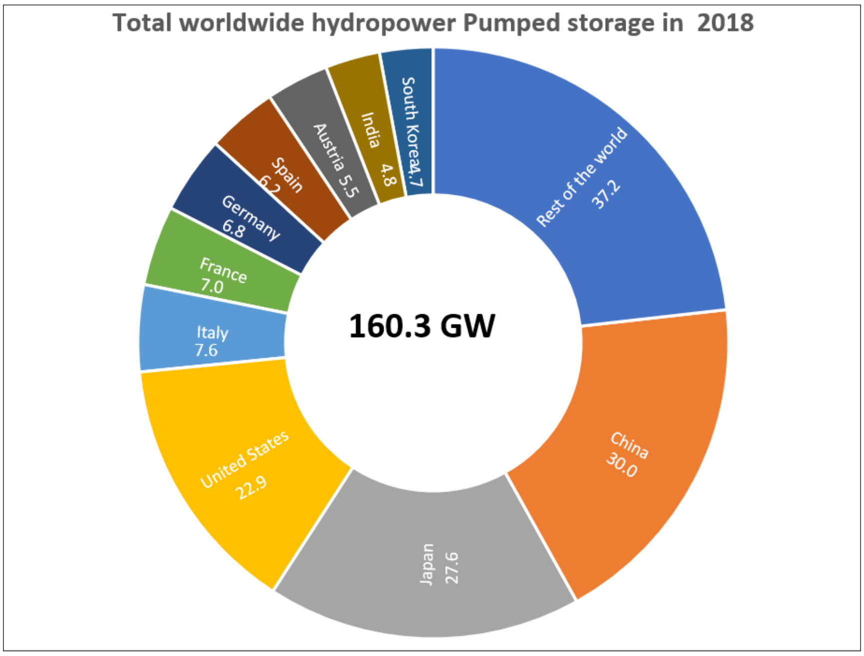


Figure 11: Pumped hydropower storage capacity in GW of the top 10 countries and the rest of the world in 2018 (IHA,2019).

According to the hydropower pumped storage tracking tool, online resource on the world's water batteries launched in November 2017, there are 100 planned PHES projects with 75 GW capacity. These planned projects will increase the global storage capacity by 50 percent to reach almost 225 GW by 2030 (IHA, 2019).

C. Seawater Pumped storage

1. Overview

Seawater Pumped Storage (SPS) system is a modified form of PHES. They are built on coastal mountainous topography harnessing seawater. Only an upper reservoir needs to be built and the sea is used as the lower reservoir. The SPS system work scheme is the same as the conventional PHES system and it possesses a round trip efficiency of about 80-85%. During off-peak hours, the turbine operates in pumping mode to transfer seawater to the upper reservoir. Then during peak-hours, seawater is let free to flow through the penstock reaching the turbine in the powerhouse to generate electricity before being discharged into the sea.

Seawater pumped storage system possess some advantages in comparison with the conventional pump hydro-electrical storage system and they can be summarized as followed:

- The construction cost is reduced since only one reservoir needs to be built.
- The use of seawater instead of freshwater reduces the pressure on freshwater demand and water scarcity.
- The abundant availability of seawater allows a larger storage capacity for the upper reservoir thus large-scale power stations can be built.
- The low head variation is an advantage for the pump-turbine design. The water surface level of the lower reservoir, i.e., sea, only varies between low and high tides.
- There is an advantage of power transmission and system operation when a suitable site location is selected near the power demand area or the baseload power supply plant.
- Besides the advantages of SPS, it is necessary to find concrete solutions for technical problems that arise from the use of seawater and problems of environmental impacts. These problems are summarized as follows (Hiratsuka et al., 1993):
- Corrosion of metal material by use of seawater. This necessitates the use of corrosion-resistant materials for hydrodynamic equipment such as pump-turbines and penstock. And also, anticorrosion countermeasures should be secured for durability, economy, and easy maintenance.

- Adhesion of marine species such as shellfish and seaweed on hydrodynamic equipment (for example exposed surface of intake, outlet, penstock, etc.). This reduces the cross-sectional area of the tube and increases its roughness leading to a reduction in the overall efficiency of the SPS plant.
- Environmental impacts due to the leakage and infiltration of seawater from the upper reservoir or the penstock into the underground.
- Spread of seawater from the upper reservoir by the wind. The dispersion of saltwater to the surrounding vegetation can cause damage.
- The effects of the seawater intake from and discharge to the sea on the marine organisms and the disturbance of existing local currents around the outlet bay.

Today, only one SPS plant was implemented worldwide for power peak shaving in Okinawa, Japan. However, there are plans for larger facilities in Ireland and Hawaii (Akinyele & Rayudu, 2014).

2. Existing SPS project: SPS power plant in Okinawa, Japan

The main experience with SPS power plants is the 30 MW plant located in Okinawa Island, Japan (Hiratsuka et al., 1993). It is considered as an important information source for studying the feasibility of the construction and operation of similar projects.

The Ministry of International Trade and Industry (MITI) of Japan has been conducting surveys, since 1960, about suitable sites for SPS plant. As of 1981, the Electrical Power Development Co., Ltd. (EPDC), by the entrust contract with MITI, started conducting feasibility surveys and researches on seawater pumped-storage power generation technology and its environmental impacts. Once the feasibility of an

SPS project was confirmed, MITI decided to build a pilot plant in Okinawa and to put it after construction under test operations for five years. The Okinawa pilot plant construction by EPDC began in 1991 costing ¥[1] 3.2 billion. Then it was put under test operations starting March 17, 1999. The plant operated for more than 10 years, however, since the demand for electric power in Okinawa had not grown as predicted the plant was dismantled in 2016 (Experimental power plant in Kunigami dismantled, 2016).

a. Outline of the plant

The Okinawa seawater power plant faces the Pacific Ocean which represents the lower reservoir (J-POWER, 2001). The plant utilizes an effective head of 136 meters and it generates a maximum power of 30 MW, using a maximum seawater flow of 26 m3/s.

The upper reservoir is located on a plateau 150 meters above sea level and 600 meters from the coast. Its shape is octagonal, 25 meters deep, and 252 meters across. Moreover, it has an effective storage capacity of 564,000 m3.

The landscape of the area was preserved by installing underground the penstock, powerhouse, and the tailrace. Where the powerhouse is located 150 meters underground and is installed in a cavern 17 meters wide, 32 meters high, and 41 meters long.

The energy needed for pumping-up seawater will be transmitted by a transmission of 66kV constructed over a distance of 17 km. The transmission line connects the power plant with the Taiho Substation of Okinawa Electric Power Co., Inc. (Hiratsuka et al., 1993).

[1] 1 USD= 138 ¥, exchange rate of 1991 (Dollar Yen Exchange Rate (USD JPY) - Historical Chart, 2020)

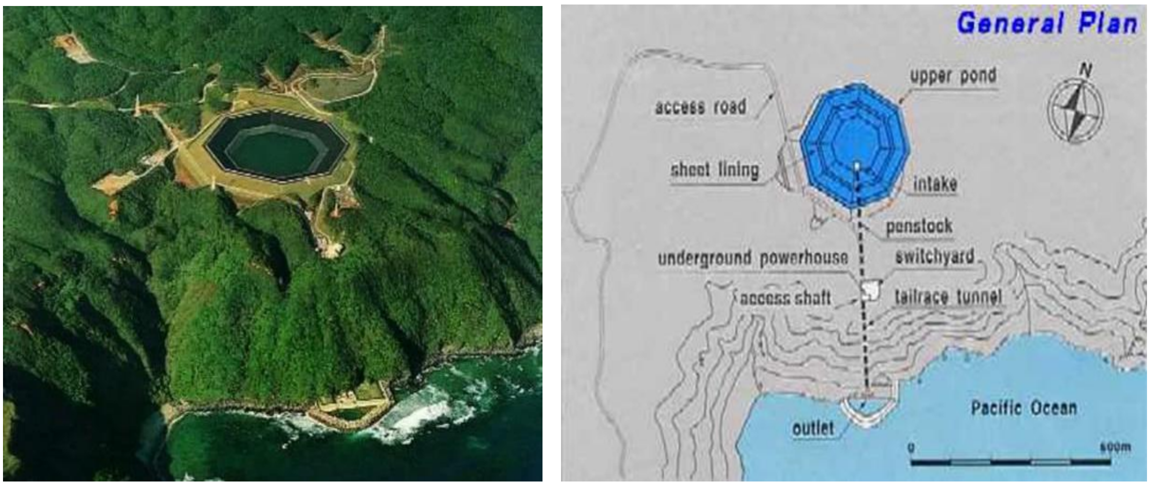


Figure 12: Okinawa Japan SPS plant outline (Hiratsuka et al., 1993).

D. Pumped hydro storage plants in Lebanon

There is no pumped hydro storage plant yet in Lebanon. However, according to a study done by Geadah (2009), a senior hydraulic engineer and consultant to Litani River Authority, nine potential sites were found for introducing pumped storage in Lebanon amounting to a capacity of over 1100 MW. Among the 9 sites, 6 are located along sea-shore and the remaining are inland. Among the identified seashore site, one site is of the turkey-nest type, which is a man-made artificial reservoir, and it is located in Ras Ech Chaqaa. The remaining sites are of the dammed-valley type, which is a natural topographical depression or valley land used in conjunction with a dam to form the water storage reservoir.

Table 6 provides data on identified potential sites. The sites were ranked based on their advantages and disadvantages determined from technical, financial and environmental indicators. Figure 13 shows the location of the sites on the Lebanese map.

Table 6: Lebanon's Pumped Storage Master Plan: Data of Identified Typical Potential Projects (Geadah, 2009).

Category Type	Project		Generating Capacity (MW)	Expected Annual Peak Generation (GWH)	Base investment Cost (Million USD)	Estimated Pay Back Perriod (Year)	Rank
Inland/ Qaroun Lake/ Litani River	Qaroun Lake-Marj Et Taouil		388	713	565	20	2
Inland/ River Basin Dam	Hasbani River-lbl Es Saqi Dam		21	37	34	31	4
Inland/Perennial Spring – Hill Lake	Hammana- El Mghiti		12	9	31	35	5
Sea Shore / Coastal Cliffs	Ras Ech Chaqaa		30	54	50	37	5
	Ouajh El Hajar		33	60	52	16	1
	El Jiueh		225	405	344	16	1
	Ras Nabi Younis	Alt.1*	234	421	348	18	1
		Alt. 2	221	398	351	23	3
	Ras El Bayada		90	163	135	18	1
	Ras Ed Draijat		140	252	219	20	2

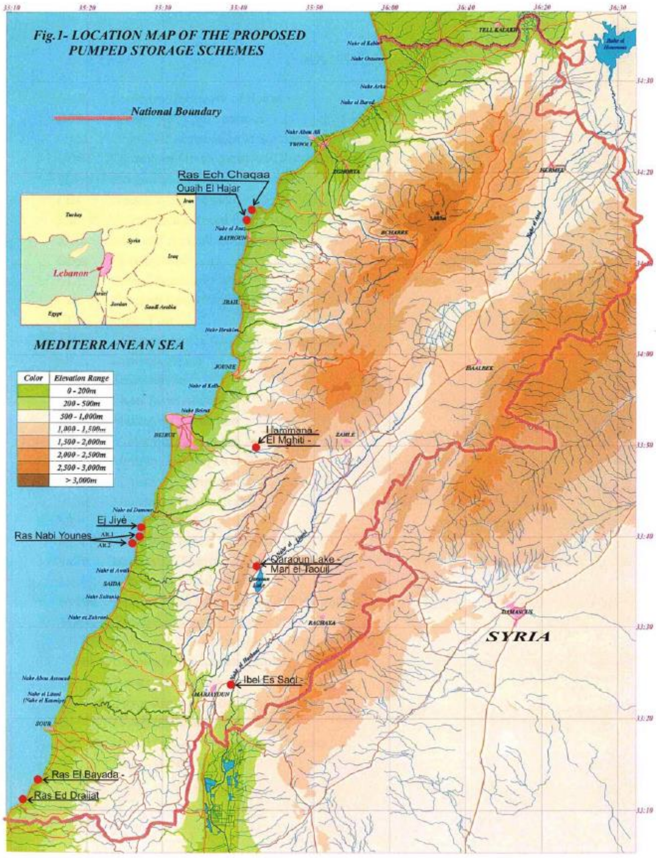


Figure 13: Location map of the proposed pumped storage schemes (Geadeh, 2009).

CHAPTER III

PRELIMINARY SITE SELECTION OF SEAWATER PUMPED STORAGE PLANTS IN LEBANON USING A GEOGRAPHIC INFORMATION SYSTEM (GIS) BASED APPROACH

This chapter illustrates the analysis approach used in the Geographic Information System (GIS) software to find preliminary sites for a seawater pumped storage plant near the Lebanese coastline and to quantitatively assess their potential power and storage capacity.

A. GIS applications for site selection

The process of selecting a site that is both technically and commercially feasible as well as socially acceptable is a critical stage in assessing the SPS potential in Lebanon. The conventional method of PHES plant site selection has limitations and is not viable in terms of cost and time (Ahmadi & Shamsai, 2009), thus there is a need for accurate, simple, and economical methods to identify feasible sites.

Geographic Information Systems (GIS) are considered important tools that improve spatial data visualization and analysis. Using a GIS based suitability analysis would be helpful for site selection since it allows for the evaluation of sites based on criteria. Moreover, GIS provide a range of analysis tools that helps create a defined analysis model.

Several GIS-based studies focused on locating sites for the development of hydroelectric or PHES projects. Carroll et al. (2004) used GIS tools to identify potential small hydropower sites in the USA. Ahmadi et al. (2009) used a GIS-based approach for preliminary site selection of PHES plants and concluded that this method saves time and cost compared to the conventional approach. Moreover, Larentis et al. (2010) developed a GIS-based computational program for a large-scale survey of hydropower potential sites in Brazil. More recently, Jiménez Capilla et al. (2016) generated a multi-criteria GIS-based analysis to identify existing dam sites that can be retrofitted into a PHES system. The criteria incorporated in the analysis were topography, land use, geology, and meteorology. Lu & Wang (2017) studied the PHES potential in Tibet by finding potential PHES station sites using Geographic Information Science (GIS) analyses.

B. GIS analysis methodology

The proposed GIS analysis to locate potential SPS plant site consists of the following steps:

- Defining the decision factors and criteria.
- Preparing the spatial data needed and assigning a layer for each criterion.
- Generating an analysis model using ModelBuilder.
- Computing the power capacity value of the selected potential sites for SPS plant.

1. Definition of SPS site selection factors and criteria

Six criteria are used to explore SPS potential sites. According to Katsaprakakis et al. (2013), satisfying these parameters: (i) ensures the technical and economic feasibility of the SPS plant and (ii) decreases the technical work required leading to a lower investment cost. These criteria were divided into three groups: techno-economic factor, social/environmental factor and infrastructure factor as shown in the diagram, Figure 14. Moreover, the diagram includes the threshold value of each criterion.

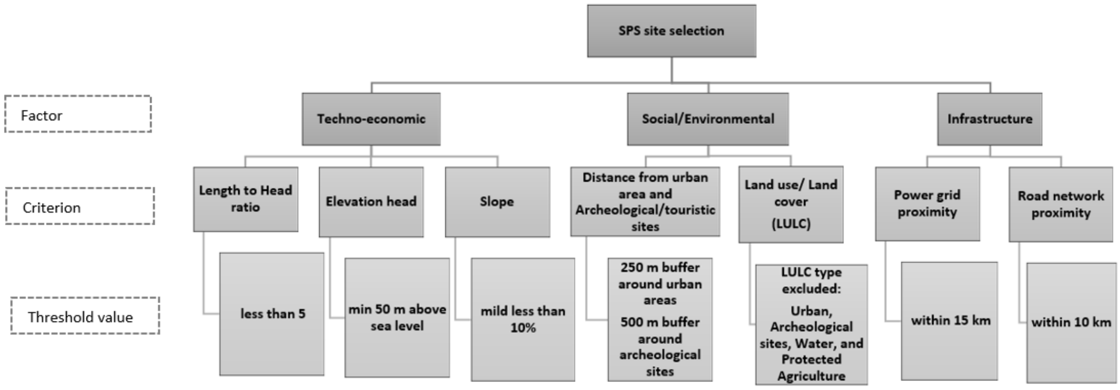


Figure 14: Tree-structure of the factors, criteria, and threshold value of the SPS preliminary site selection.

a. Techno-economic factor

Length to head ratio: is the ratio of the penstock length (L) over the absolute altitude difference between the penstock's ends (H). As the head increases, the length of the waterway increases. Consequently, a smaller L/H is more economical since for the same head the conveyance length is less. According to Namgyel (2012), for low-head sites, elevations between 150 and 180 m, the maximum L/H ratio value ranges from 4 to 5. Therefore, in this study, the potential SPS site in search should possess a small length to head ratio. We defined a cutoff value of 5 as the maximum value for L/H.

Elevation head: the altitude above sea level is a crucial characteristic since it determines the capacity of the SPS site. This search only included the sites having at least 50 meters altitude above sea level to ensure that the potential SPS site power capacity is at least 10 MW. The power capacity equation, found in section 5.2, was used, to estimate this minimum head value.

Slope: having a flat area, mild slope, facilitates the construction of the artificial reservoir and reduces the cut and fill costs. Therefore, the slope of the site's natural ground should be mild with a value of less than 10%.

b. Social/Environmental factor

Distance from urban area and archeological/touristic sites: a reasonable distance should be observed in order to reduce public objection, reduce visual intrusion and prevent negative reactions from local community against the construction and operation of SPS plant. Therefore, the potential site must be located at least 250 m and 500 m away from urban areas and archeological/touristic areas, respectively.

Land use/Land cover (LULC): the absence of activities in the area is a must to ensure that the potential SPS site is socially and environmentally acceptable. Therefore, certain area types of land cover/ land use were dismissed from this study (Urban, Archeological sites, Water, and Protected Agriculture).

c. Infrastructure factor

Power grid proximity: the site must be located in the vicinity of the existing power grid. Having existing power lines close to the site allows: (i) to transmit the electricity produced by hydro turbines to the national grid, and (ii) to receive electricity to power the pump during off-peak hours. Moreover, the closeness to the power grid lines decreases the connection costs. Thus, the site must be within 10 km of an access road.

Road network proximity: the site should be located near access roads. This will facilitate the access to the SPS plant site for construction and operation purposes. Therefore, the site must be within 15 km of a power grid lines.

2. *GIS analysis model*

The model utilizes geographic data and the prescribed site selection criteria to recognize potential SPS sites. It was built within ArcGIS10.6.1 using ModelBuilder which is a visual programming language for building geoprocessing workflows.

a. <u>Preparation of the spatial data and criterion layer</u>

Before starting the analysis, all the vector data (Lebanese shoreline delineation, Lebanon boundaries, roads network, electric grid network, and Land use/Land cover) were projected into the UTM36 geographic projection system. Then, for the spatial analysis, the vector data were converted into Raster type with a 50 m cell size.

The elevations above sea level were identified using the digital elevation model 50 meters cell size (DEM50). First, the cells having an elevation smaller than 50 meters were set to null. Then, to obtain only elevations within 2 km of the shoreline; the produced elevation raster was extracted by mask using the Euclidean distance raster of shoreline, with a maximum distance of 2 km, as the mask feature. In that way, the elevation of cells located more than 2 km of the shoreline will hold a NoData value.

The length to head ratio, L/H, was computed using raster analysis. Where L was taken as the nearest distance between a cell and the seashore, this value was obtained using the Euclidean distance tool. And H is the elevation of the cell found from the Dem50 raster.

The ground slope was generated from the Dem50 raster using the slope tool under the surface tool from the spatial analyst toolbox. Then, the cells having a slope value of more than 10% were set to null.

The distance from a cell to the closest access road and to the closest grid lines was found using the Euclidean distance tool.

b. Reclassification and assignment of suitability rank values to each criterion

The criterion layers produced were reclassified into 3 classes using Jenks natural breaks classification. This classification method was chosen because it divides the data into homogenous classes and maximizes the difference between the classes (Jenks, 1977). Then these classes were given a suitability score varying from 1 to 3 with 1 being the least preferable.

i. Elevation Head

The elevation head raster was reclassified as shown in Table 7. The power generated from the SPS plant is dictated by the head and discharge values. A higher head leads to a higher water pressure across the hydro turbine resulting in more power generation. Therefore, higher head values are scored more.

Table 7: Suitability score given to Head (m) value classes.

H (m)	Suitability Score
50 - 100	1
100 - 230	2
> 230	3
NoData	NoData

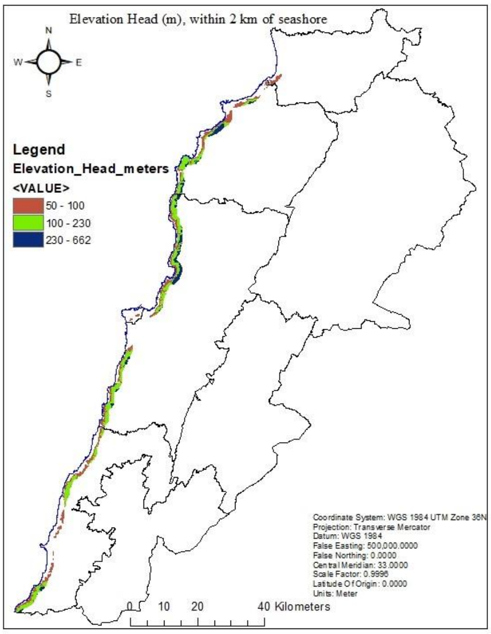


Figure 15: Elevation head (m) within 2 km of shoreline.

ii. Length to head ratio (L/H)

The cells with an L/H of more than 5 were set null, and the remaining cells were reclassified and scored as specified in Table 8. The smaller L/H ratio is assigned with a higher score since a small L/H is preferable.

Table 8: Suitability score given to L/H ratio.

L/H	Suitability Score
0 - 2.5	3
2.5 - 4	2
4 - 5	1
NoData	NoData

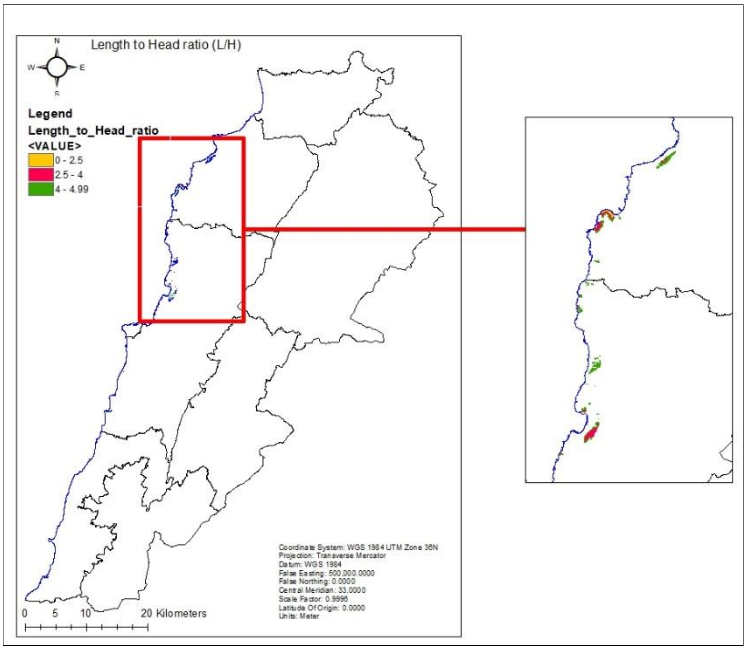


Figure 16: L/H ratio < 5.

iii. Slope

The cells having a slope value of more than 10% were set to null. The output raster was reclassified as shown in Table 9. Since a flat area is more economical, smaller slopes were given higher scores.

Table 9: Suitability score given to slope (%) value.

Slope (%)	Suitability Score
0 - 3	3
3 - 6	2
6 - 10	1
NoData	NoData

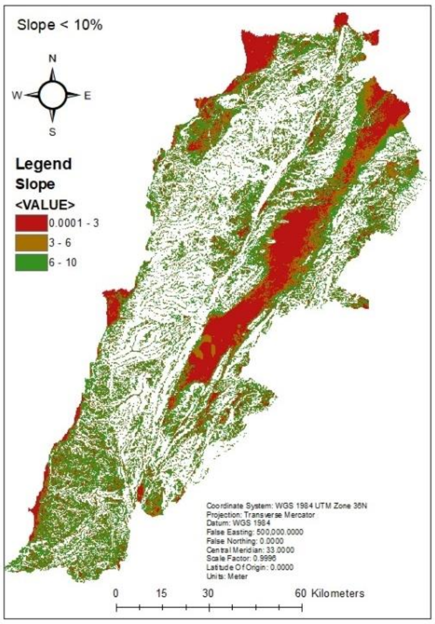


Figure 17: Slope less than 10%.

iv. Land use/Land cover (LULC)

The cells corresponding to the land cover/ land types dismissed from this study were assigned a NoData value. The remaining area types were assigned a score depending on their suitability. A higher score is given to the more suitable LCLU type. The Land use/Land cover raster was reclassified as shown in Table 10.

Table 10: Suitability score given to LULC.

LULC	Suitability Score
Natural lands with no or little vegetation	3
Herbaceous vegetation	3
Agriculture	2
Burnt Wooded Lands	2
Forests	1
Urban	NoData
Archeological Sites	NoData
Water	NoData
Protected Agriculture	NoData
NoData	NoData

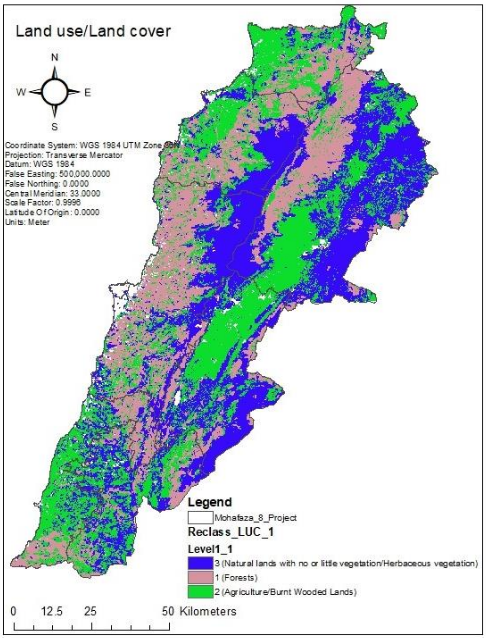


Figure 18: Land use/ Land cover classified.

v. Distance to power grid

The closer sites to the power grid scored more. The values of the distance from a site to the closest grid lines were reclassified as specified in Table 11.

Table 11: Suitability score given to distance from power grid.

Euclidean distance power grid (km)	Suitability Score
0 - 5	3
5 - 10	2
10 - 15	1
>15	NoData
NoData	NoData

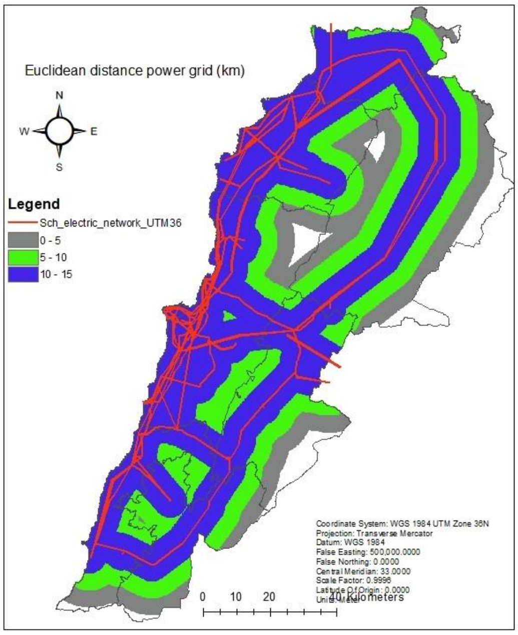


Figure 19: Distance from power grid in meters.

vi. Distance to access roads

The distances to access roads were reclassified as specified in Table 12. The higher score was assigned to the closer sites.

Table 12: Suitability score given to distance from roads.

Euclidean distance roads (km)	Suitability Score
0 – 2	3
2 – 5	2
5 - 10	1
>10	NoData
NoData	NoData

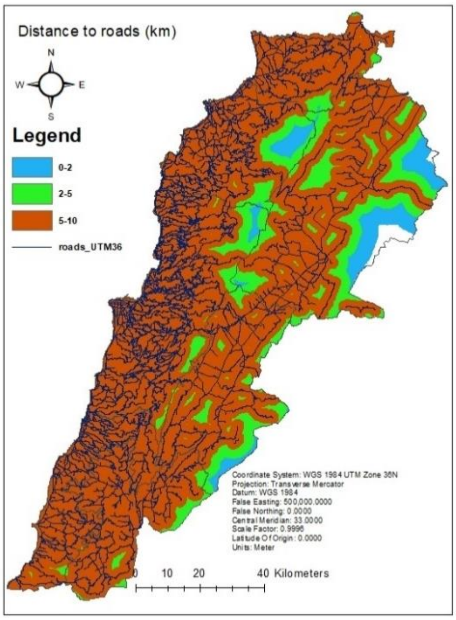


Figure 20: Distance to access roads in meters.

3. Criteria weighting

Previous studies incorporated several criteria to explore suitable sites for PHES and SPS plants. These criteria do not have the same effect on the PHES/SPS site selection. Therefore, a weight is given for each criterion to reflect its cost and value compared to the other criteria. Table 13 presents the weights of all criteria used in this analysis. They were assumed based on literature review and previous applications, such as the work of Ahmadi et al. (2009) which used the Knowledge Driven Weighting method that relies on expert experience about PHES application, to determine the weights of the site selection criteria.

Table 13: Weight of selection criteria.

Factors	Criteria	Weight (%)
Techno-economic factor (65%)	Head (Elevation difference), m	20
	Length to Head ratio (L/H)	25
	Mild slope of natural ground, %	20
Social/Environmental factor (15%)	Land use/Land cover	15
Infrastructure Factor (20%)	Power grid proximity, km	10
	Road network proximity, km	10

4. SPS site scoring method

The last step in the GIS analysis model is to determine the total suitability value of any region. The raster calculator tool was used to generate the weighted average scoring of each region based its score and criterion weight. Figure 21 illustrates the site scoring process.

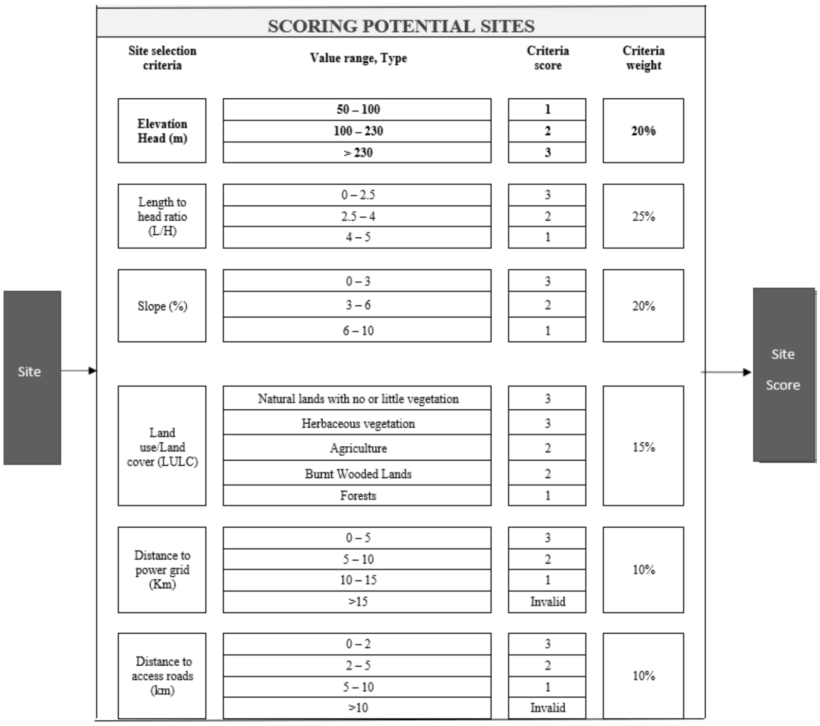


Figure 21: Site scoring method.

5. Site identification

Ideally, the site suitability scoring should vary between 1 and 3, where 3 is the most favorable. However, the output raster showed that the maximum suitability score was 2.75, meaning no site matched the highest score of the six criteria simultaneously.

The final site scoring values were ranked from 1 to 3, with 1 being the least preferable. The score of areas with a value between 1.7 and 2.25 was set as 1, a score between 2.25 and 2.5 was set as 2, and a score between 2.5 and 2.75 was set as 3. However, the areas with a score below 1.7 were discarded since they were considered to have low suitability.

After that, the reclassified raster was extracted into polygon feature data to be used for quantitative analysis. The potential sites areas overlapping with the buffer layer around urban area and archeologic sites were eliminated.   Then, the polygons having an area greater than 50,000 m2 were only selected to ensure that enough land is available to build the SPS plant’s upper reservoir.

As a result, two SPS upper reservoir potential sites were identified, and they are located in the North Lebanon Governorate. Figure 22 shows the location of the two potential sites.

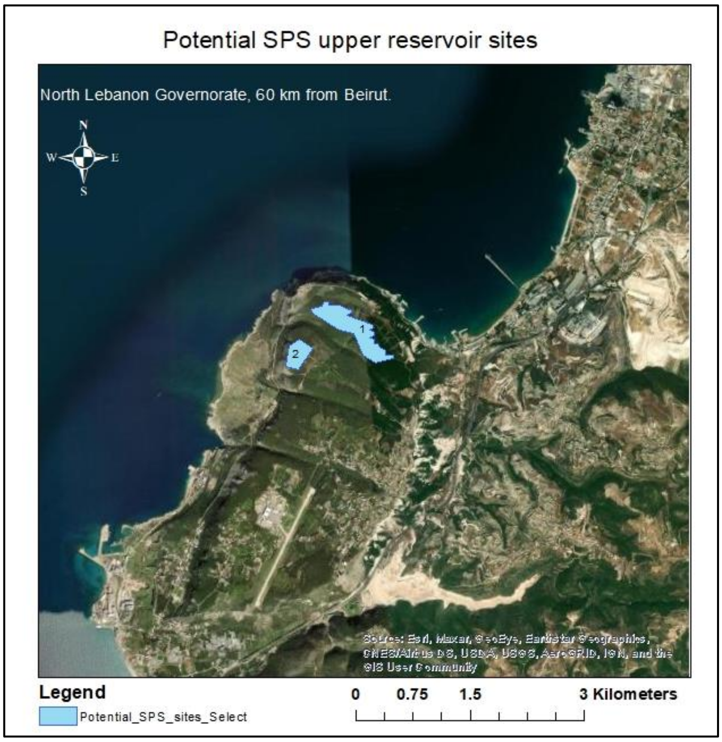


Figure 22: Potential sites, Site 1 and Site 2, for SPS plant upper reservoir.

Finally, the Zonal statistics tool was used to identify the mean value of the potential sites' characteristics such as the L/H ratio, elevation head, slope of natural ground, distance from access roads, and the distance from the power network lines. Table 14 summarizes the characteristics of each potential site.

Table 14: Characteristics of potential sites.

Characteristics	Site 1	Site 2
Location	35°41'15.735"E 34°18'31.703"N	35°40'58.638"E 34°18'17.996"N
Area (m^2)	269,433.79	88,794.34
L/H	3.12	4.25
Head (m)	170.7	173.71
Slope (%)	5.52	4
Distance from seashore (m)	533	739
Distance to access road (m)	468.66	365.95
Distance to power network (m)	944.73	960.87
Suitability score	2.01	1.91

6. Potential power capacity calculation

The power generated from the SPS potential plant sites is calculated using the power capacity equation, (Connolly, 2010), presented in Chapter 2. For this study, the seawater density is taken as 1025 kg/m^3, flow rate as 26 m^3/s (Oshima et al., 1999), and the efficiency as 0.8 (Zipparro & Hasen, 1993). Therefore, Site 1 and Site 2 possess a potential power capacity of 35.7 MW and 36.3 MW, respectively;

Site 1 : $P = \eta \times \rho \times g \times Q \times H = 0.8 \times 1025 \times 9.81 \times 26 \times 170.7$
$= 35.7\ \text{MW}$

Site 2 : $P = \eta \times \rho \times g \times Q \times H = 0.8 \times 1025 \times 9.81 \times 26 \times 173.7$
$= 36.3\ \text{MW}$

7. Reservoir sizing

The proposed SPS plant aim is to support the national grid during peak-hour electricity demand, in order to decrease the range of energy needed through power shifting. Referring, to the daily electricity load curve of Lebanon (EDL, 2015), the peak demand hours are from hour 17 until hour 22. Therefore, the SPS guaranteed power will be produced for five hours daily.

The daily storage capacity of the plant is 178.5 and 181.5 MWh for Site 1 and 2 respectively, which is the power capacity of site multiplied by the plant operation hours. Then, the volume of water that is drained and filled each day is 415,979.394 and 415,641.52 m^3, for Site 1 and 2 respectively, and it is determined from the energy storing capacity equation (Connolly, 2010). The turbine efficiency is 0.9 (Zipparro & Hasen, 1993).

Site 1: $SC = \frac{\rho \times g \times H \times V \times \eta T}{3.6 \times 10^9} = \frac{1025 \times 9.81 \times 170.7 \times V \times 0.9}{3.6 \times 10^9} = 178.5\ \text{MWh}$
$\Rightarrow V = 415{,}979.394\ m^3$

Site 2 : $SC = \frac{\rho \times g \times H \times V \times \eta T}{3.6 \times 10^9} = \frac{1025 \times 9.81 \times 173.71 \times V \times 0.9}{3.6 \times 10^9} = 181.5\ \text{MWh}$
$\Rightarrow V = 415{,}641.52\ m^3$

8. Sensitivity analysis and discussion

Sensitivity analysis (SA) was used to evaluate the impact of changes in model parameters on model predictions. The analysis consists of running the model while changing the criteria weights and tracking the changes in the output. Two iterations were carried out. The first scenario consists of giving equal weights to all the criteria. And, the second scenario gives 40% weight for both the Social/Environmental factor and Techno-economic factor.

Table 15: Sensitivity analysis scenario's weights.

Factors	Criteria	Weights		
		Adopted scenario	Scenario 1	Scenario 2
Techno-economic factor	Head (Elevation difference), m	20	16.67	20
	Length to Head ratio (L/H)	25	16.67	10
	Mild slope of natural ground, %	20	16.67	10
Social/Environmental factor	Land use/Land cover	15	16.67	40
Infrastructure Factor	Power grid proximity, km	10	16.67	10
	Road network proximity, km	10	16.67	10

The iteration results showed that the same areas were selected as shown in Figure 23. Therefore, the model is considered not sensitive for parameter changes.

Figure 23: Sites identified from the 3 scenarios.

CHAPTER IV

FURTHER SITE INVESTIGATION

In this chapter the site suitability will be further assessed in terms of the following aspects: environmental/social, land ownership, geotechnical and water table vulnerability. Moreover, it will include the preliminary design of the upper reservoir and a geotechnical analysis.

A. Wetlands

Deir El Nouriyeh cliffs of Ras Chekaa is a wetland site under Ramsar Convention (MOE & IUCN, 2012). It is located in Chekaa, North Lebanon Governorate, 60 km from Beirut, with geographic coordinates of 34º 18’ 47.56” N latitude and 35º 40’ 58.03” E longitude. The reserved land is constituted of limestone cliffs adjacent to the sea with hard underwater bottoms and caves and has an area of 0.85 km^2 (Ramsar, 2012). This wetland is of cultural and religious importance and its presence serves two main purposes: (i) economic for agriculture and fishing activities and (ii) religious and touristic due to the presence of the convent of Deir El Nouriyeh. Figure 24 shows in red the delineation of the Deir El Nouriyeh cliffs of Ras Chekaa wetland (MOE & IUCN, 2012). As Site 1 area intersects with the reserved land it is discarded from this study.

Figure 24: Ras Chekkaa, delineation of proposed study site by Shaban at al. (2016) and RAMSAR site (Google Earth, 2021).

A study by Shabanet al. (2016) investigated the Cliffs of Ras Chekkaa along the northern coast, Mazra'at Hanouch, as a wetland area. The site is located 45 km from Beirut and extends between the following geographic coordinates 34° 17' 38'' N and 34° 18' 43'' N latitude and 35° 40' 10'' E and 35° 40' 48'' E longitudes. It is a plain area surrounded by mountain hills. Figure 24 shows the delineation of this area in yellow (Shaban et al., 2016). This study used three pillars with subitems as wetland criteria to characterize the proposed area. The three pillars are water availability, species uniqueness, and state of knowledge. As shown in Table 16, this site possesses a limited number of flora and fauna, and a poor hydrological feeding mechanism. This investigation showed that the proposed Ras Chekkaa site poorly meets the wetland criteria; it obtained a low score of 14/100 for wetland criterion. Therefore, the access to the sea from Site 2 that passes through this area can be secured.

Table 16: Characterization of Ras Chekkaa studied wetland site.

	River	Spring outlet	Natural lake	Seepage from rocks	Piezometric	Saturated soil	Long-term soil	Unique flora species	Abundant unique flora	Unique fauna species	Abundant unique fauna	Reserved	RAMSAR	Natural	Proposed
	Primary criteria (10 points maximum)							Secondary criteria (5 points maximum)				Proposed criteria (2.5 points maximum)			
Well exists													✓		
Normally exists										✓					
Poorly existing				✓		✓		✓							

B. Land tenure and ownership

The lands within the Ramsar site, which are comprised of the cliffs of Ras Chekaa adjacent to the sea and the agricultural areas surrounding the Deir El Nouriyeh convent of Saidet El Nouriyeh, are the private property of the convent. The marine part of the wetland is owned by the Lebanese government. The areas outside the reserved land and surrounding Ras Chekaa are also private properties belonging to the convent of Saidet El Nouriyeh (Ramsar, 2012). And the villages of Hamat and Ouajh El Hajar are public or private properties.

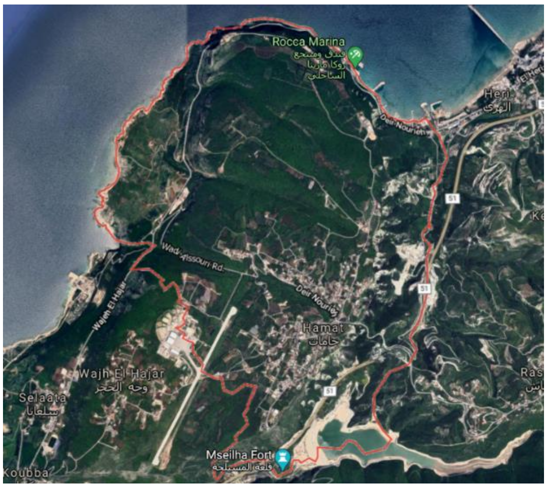


Figure 25:Deir El Nouriyeh properties (Google Earth, 2021).

C. Geology and topography of site

The stratigraphic sequence of Ras Chekkaa is made out of three major geological rock formations. They are present in the area extending from the Ramsar site to the adjacent cliffs and upward to the entire region of Hamat and the villages of Deir EL Nouriyeh as presented in Figure 26 (Dubertret, 1953).

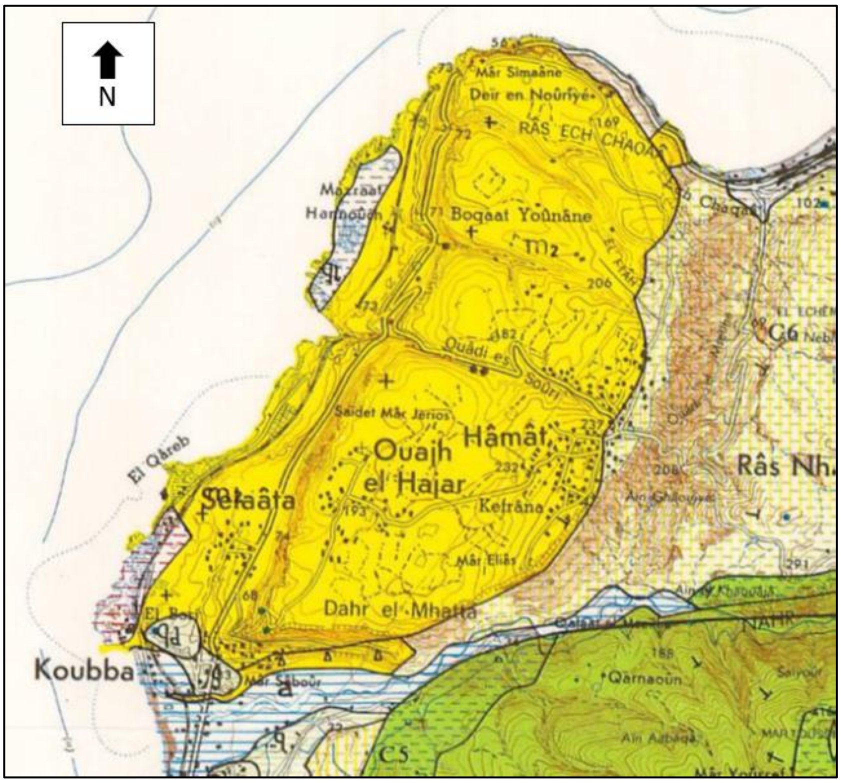


Figure 26: Geological map of Ras Chekkaa and the surronding (Dubertret, 1953).

The three geologic rock formations are illustrated in Figure 27. They are listed chronologically from the younger to the older as follows (Shaban et al., 2016):

- Quaternary deposits (Q): This constitutes a maximum thickness of 15 m from sea level. The layer is made of unconsolidated sediments with alluvial and colluvial deposits. It is dominated by red sandy soil with some sandy terraces. Moreover, movable dunes are present in different regions.
- Miocene Marly Limestone (m2): It compromises a thickness of less than 150 m. It is composed from massive, moderately hard, thick-bedded yellowish-beige

marly limestone with many local fissures and joint system. It forms the mountainous ridge extending from Daher Al-Mahhatta from the south to Dier El Nouriyeh in the north (Figure 26).

- Senonian Marl (C6): this layer comes with variable thickness in the area of study varying from 80 to 100 m. It is constituted from unconsolidated and movable marl with beige color. Therefore, the fragility and softness of these rocks make the region similar to a badland with little uniformity. The Senonian Marl formation shapes the east side of the Miocene formation.

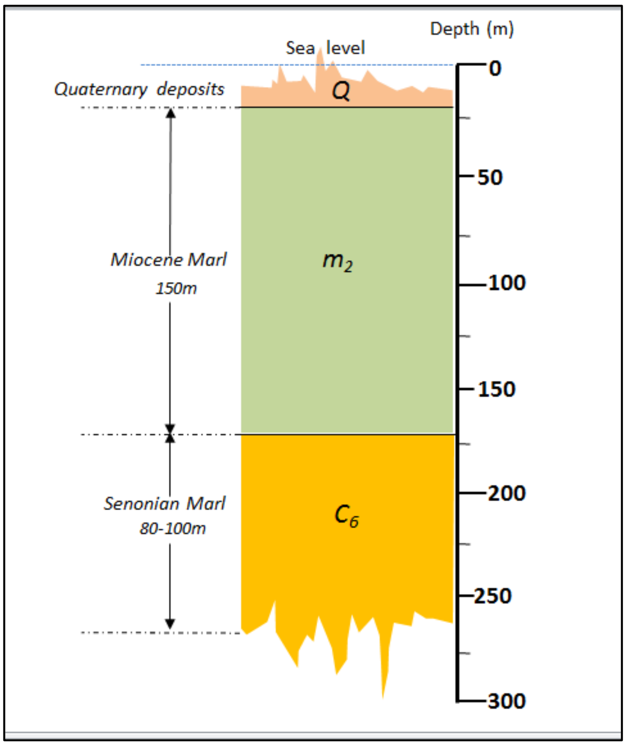


Figure 27: Stratigraphic sequence of Ras Ech-Chekkaa site (Shaban et al., 2016).

Table 17 summarizes the properties of soil/rock types considered representative of the present strata at Ras El Chekaa site. These values were used in Sadek & Hamad (2007) study that assessed the structural safety of the Chekka tunnels.

Table 17: Soil and rock layers parameters (Sadek & Hamad, 2007).

Material	Wet Unit Weight (kN/m^3)	Saturated Unit Weight (kN/m^3)	Menard Modulus (MPa)	Cohesion (kPa)	Friction Angle (degrees)
Soil	18	20	10	40	30
Soil, soft marlstone	20	22	35	60	25
Intact marly-limestone rock	20	22	100	200	35

The cliffs that surround the massive ridge at the eastern side are attributed to fault alignment and the cliffs at the northern side are attributed to rotational landslides (Shaban et al., 2016). This fault is of normal type and it constitutes the Ras Chekka cliff and extends in the north-south directions with a vertical displacement of 100-120 m.

In the massive marly limestone, fissure systems are dominant and joints of 2-sets type are present at different depths with a north-south orientation (Shaban et al., 2016).

D. Water table vulnerability

The groundwater depth in Chekka varies between 10 and 35 m (UNDP, 2014).

E. Reservoir design and geotechnical analysis

As mentioned in a previous chapter, the required water storage volume, of the upper reservoir at Site 2, is 415,641.52 m3. The groundwater depth is assumed as 10 m, a worst-case scenario. Therefore, the artificial reservoir is designed to have a depth of 8 meters, and a surface area of 51,955.19 m2. This land area is available since Site 2 possesses a total area of 88,794.34 m2. The artificial reservoir shape is hexagonal, as shown in Figure 28.

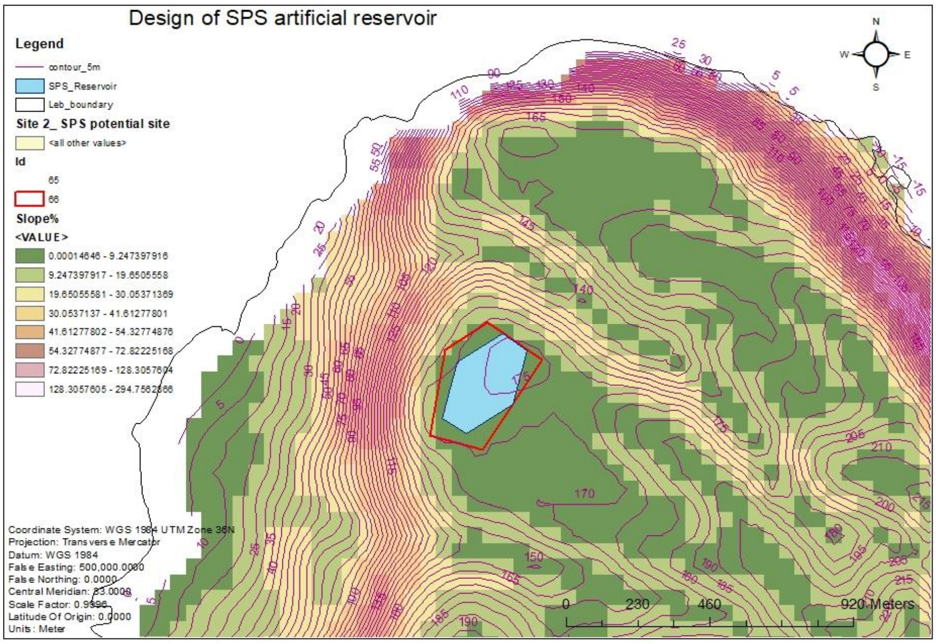


Figure 28: SPS upper reservoir, area 52,000 m2, Site 2 (GIS analysis).

The settlement of the land subject to the reservoir load was assessed using Settle3D software. Settle3D is a program used for analyzing the settlement and consolidation under foundations, embankments, and surface excavations. The software calculates three-dimensional stresses due to surface loads. However, displacements or settlements and pore pressures are computed in one-dimension, assuming only vertical displacements can occur.

First, the reservoir was drawn into scale in Settle3D as an excavation with a depth of 8 meters. A disturbed load was assigned at the bottom of the excavation with a value of 125 Kpa, which corresponds to weight of seawater and reinforced concrete and 1.2 factor of safety. This load was calculated as follows:

$$\text{Load from seawater} = \rho\left(\frac{\text{kg}}{\text{m}^3}\right) \times \text{depth(m)} = 1025 \times 8 = 8200\ \left(\frac{\text{kg}}{\text{m}^2}\right)$$

$$= 80.36\ \text{Kpa}$$

$$\text{Load of reinforced concrete} = \rho\left(\frac{\text{KN}}{\text{m}^3}\right) \times \text{depth(m)} = 24 \times 1 = 24\ \text{Kpa}$$

$$\text{Total load} = 1.2\ \times (\text{Load from seawater} + \text{Load of reinforced concrete})$$

$$= 1.2\ \times (80.36 +\ 24) = 125\ \text{Kpa}$$

Then, the soil layers were defined, a 5m top soil (soft marlstone) layer followed by a 75 m intact marly-limestone rock layer. The soil parameters, unit weight and Menard Modulus, were inputted as pacified in Table 17.

The analysis showed that the settlement at the bottom of the excavation, at 8 m depth, is of a maximum value of 2.5 cm. This value is considered minimal and acceptable for a reservoir structure. Therefore, the present soil condition allows the construction of the reservoir safely without causing land failure. Figure 29 shows the Settle3D analysis results.

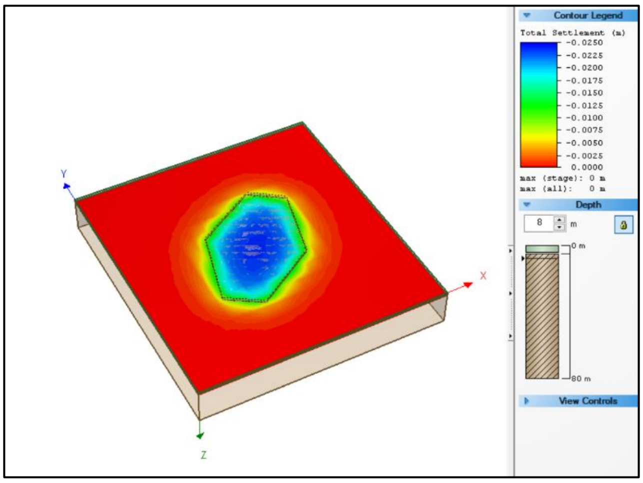


Figure 29: Ground settlement at 8 m depth (Settle3D analysis).

CHAPTER V

FACILITY DESIGN, MATERIAL AND ENVIRONMENTAL MEASURES

This chapter is about the design and material of the proposed seawater pumped storage plant. Moreover, it includes the environmental measures that need to be taken to preserve the surrounding environment. This chapter relies heavily on the Okinawa Japan SPS plant design, materials and environmental measures, since it is the only SPS plant implemented in the world.

A. Facility design and materials

The design and materials of the proposed SPS plant facility are the same as the one used for the Okinawa Japan SPS plant.

1. Upper reservoir

The following measures are used to protect the neighboring environment from the consequences of seawater leakage.

To prevent seawater intrusion, the earth-embarkment needs to be lined with an ethylene propylene diene monomer (EPDM) rubber sheet. This material possesses excellent properties and weather-resistance characteristics, and it was selected after several tests that assessed its durability, mechanical structure, water holding capacity, and ease of installation compared to alternative materials (J-POWER, 2001). The rubber sheet is easily repaired since it constitutes the reservoir base top layer.

To prevent possible leakage, a drainage layer should be constructed within the gallery of the dam structure and behind the rubber sheet (J-POWER, 2001). This layer is formed by gravel material. Moreover, seawater sensors and pressure gauges will be used to determine seawater leakage in case damage occurs to the sheet. In case of leakage: (i) an alarm signal will be initiated and will lead the pump to pump back the leaked seawater to the upper reservoir, (ii) sensors will indicate the location of leak for ease of maintenance. These sensors will be installed in the pipes connected to the drainage layer. The upper reservoir lining structure using rubber sheets of the Okinawa Japan Plant is illustrated in Figure 30 (J-POWER, 2001).

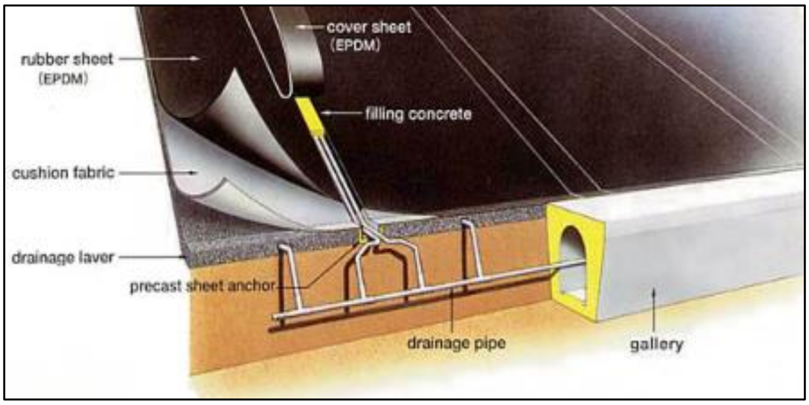


Figure 30: Okinawa SPS plant upper reservoir lining structure using rubber sheets (J-POWER, 2001).

2. Waterways

The seawater seepage into the underground is prevented by lining the penstock straight section with fiberglass-reinforced plastic (FRP), Figure 31. The FRP penstocks can withstand pressure as high as the 3136 kPa, and possess very low friction allowing a velocity of 4 m/sec (Pandey et al., 2016). Moreover, the FRP does not corrode from seawater, and based on test results, marine species can difficulty adhere to these pipes compared to the coated steel pipes (J-POWER, 2001).

The transitions will be lined by conventional steel with anti-corrosion measures. Moreover, a sleeve joint will be used as a pipe joint since it reduces the water head loss and prevents the adhesion of marine organisms. For the concrete-lined tailrace tunnel, epoxy resin coated steel bars will be used to provide corrosion resistance (J-POWER, 2001).

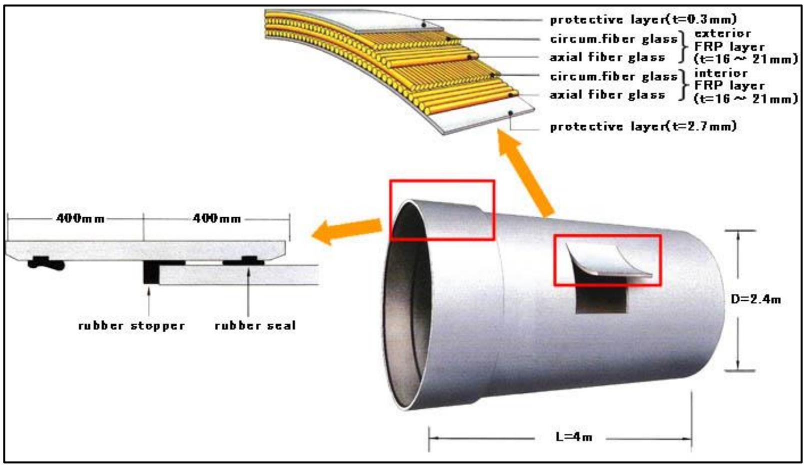


Figure 31: Structure of FRP pipe (J-POWER, 2001).

3. Outlet

The tailrace outlet will be coated with a special ceramic that possess anti-corrosion characteristics and FRP material will be used for outlet screens (J-POWER, 2001).

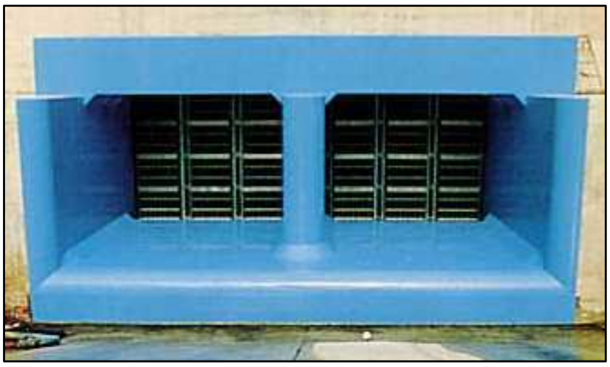


Figure 32: Surface coating of the outlet and FRP screens (J-POWER, 2001).

Around the outlet bay, a breakwater structure will be constructed by precast concrete tetrapod blocks (Hiratsuka et al., 1993). This structure helps dissipate the high ocean wave energy and prevents disturbing the local current.


Figure 33: Okinawa SPS plant outlet bay.

4. Pump-Turbine and generator-motor

A similar design of the pump- turbine developed for the Okinawa Japan plant will be used for the proposed plant. Table 18 summarizes the specifications of the SPS pump-turbine (Oshima et al., 1999).

Table 18: Specifications of the pump-turbine for SPS (Oshima et al., 1999).

Turbine operation		**Pump operation**	
Max. output	31,400 kW	Max. input	31,800 kW
Max. net head	141 m	Dynamic head	160 m
Max. discharge	26 m^3/s	Discharge	20.2 m^3/s
Specific speed	178.2 m-kW	Specific speed	51.4 m^3/s
Rotating speed	450±6% r/min		

The sectional view of pump-turbine is represented in Figure 34. The pump-turbine is easily maintained since the runner of pumped-turbine can be taken out from below leaving the turbine main parts and generator motor as they are. Moreover, the water passage surface is simplified to prevent crevice corrosion as much as possible (Oshima et al., 1999).

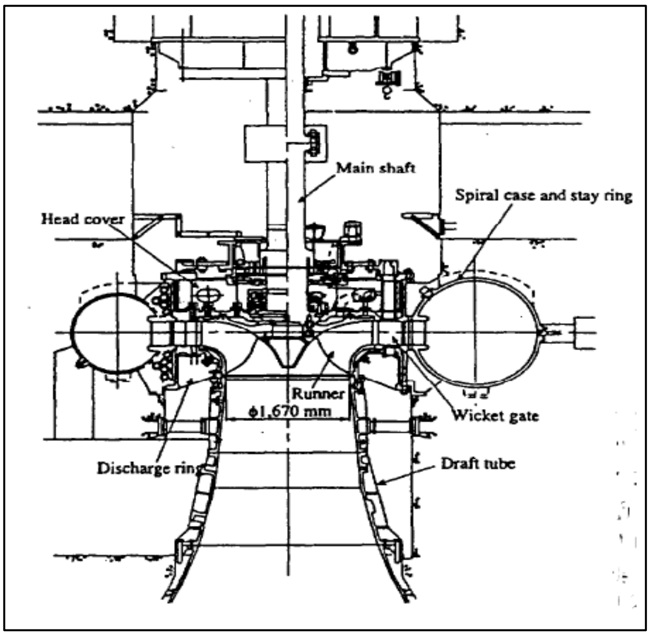


Figure 34: A sectional view of pump-turbine (Oshima et al., 1999).

The austenitic stainless-steel material will be used for the pump-turbine runner and the guide vanes since it possesses anti-cavitation and anticorrosive characteristics (J-POWER, 2001).

A variable-speed pumped storage power generation will be adopted to guarantee a high-efficiency power generation and pumping (J-POWER, 2001). The variable speed technology offers additional network flexibility compared to conventional pumped storage power generation that operates on a fixed speed only. Moreover, it allows automatic frequency control operation during pumping operation and generating operation through adjusting the revolving speed of the unit; which enables power regulation during both operations (J-POWER, 2001).

B. Environmental measures

An environmental impact assessment needs to be made before the construction of the proposed plant. Some of the environmental measures undertaken to conserve the land, sea, animals, and coral for the Okinawa Japan SPS plant will be also implemented for the proposed plant (J-POWER, 2001). These measures are listed in the following sections.

1. ***Environmental measures during the proposed SPS plant construction***

- Treating the muddy water from the earth's works to prevent its outflow into the natural streams. All the muddy water produced from the construction area needs to be stored then treated before being discharged.
- The noise and vibration of heavy construction equipment needs to be reduced to not disturb the surrounding environment. This can be achieved by using, construction machinery with low-noise type and traveling at low speed inside the construction site.
- Conservation of small animals by using fences around the construction site. This will prevent the harm of small animals from construction vehicles and accidents due to falls down to structures.

2. ***Environmental measures during the proposed SPS plant operation***

- Revegetation of the disposal yard, used during construction phase, with trees to restore the living environment for plants and animals.
- Reducing the discharge velocity used during power generation to mitigate the impact of seawater discharge from SPS plant on marine species. As mentioned before, precast concrete blocks will be used around the outlet bay structure to reduce the discharge velocity.
- Installing windbreak nets, where winds are strong, to prevent salt spraying to the surrounding environment.

3. Environmental impact assessment surveys

Environmental impact surveys need to be been made continuously before construction until the SPS plant operation years. These surveys will help monitor the effectivity of the environmental measures undertaken and to assess the impact of the plant construction and operation on the surrounding environment.

a. Terrestrial monitoring:

- vegetation before and after;
- animals: amphibians, birds and soil animals;
- noise from plant operation;
- salt content in the air around the upper reservoir;
- water quality of upper reservoir;
- salt content in underground water.

b. Marine monitoring:

- wave height and velocity in the area surrounding the outlet;
- adhesion quantity of marine organisms;
- seawater quality;
- bottom sedimentation.

CHAPTER VI

FINANCIAL APPRAISAL

A. SPS plant cost estimation

1. Investment cost

Estimating the cost of the seawater pump storage plant is the first step towards assessing the financial feasibility of the plant. Previous studies have attempted to find estimates about the investment cost of pumped hydroelectric storage (PHES) plants. The cost was estimated based on either the turbine power electricity capacity generated and expressed in terms of currency/kW, or based on the amount of maximum energy stored and expressed in terms of currency/MWh. Pina et al. (2008) estimated the investment and fixed operation and maintenance (O&M) costs of new seawater pumped storage in €/kW. Hearps et al. (2014) revised the literature about PHES costing methods and then generated a PHES costing model and named it after the Melbourne Energy Institute (MEI). The MEI costing model can be used to estimate the cost of seawater pumped storage plants. This costing model estimates the direct costs of the plant: (i) reservoir cost, (ii) piping/ tunneling cost, and (iii) electrical and mechanical costs including pumps and turbines. In addition, it estimates the indirect costs of the plant: (i) engineering, procurement, and management (EPC), (ii) contingency, and (iii) owner's costs. The MEI costing model was able to reflect the cost that relates to the horizontal and vertical distances between reservoirs, the size of water storage volume, dam construction type, and turbine/pump capacity and configuration. However, it couldn't reflect the costs that are specific to the site in terms of its geological condition and environmental constraints.

The cost of the proposed SPS plant will be estimated using both approaches, the approach of Pina et al. (2008) and the MEI costing model (Hearps et al., 2014). Then, the average cost value of two estimates will be used as the cost of the proposed plant.

a. SPS plant cost estimate based on Pina et al. (2008)

Table 19 represents the direct and indirect costs of a new SPS plant (Pina et al. 2008). It also shows the cost in term of the current dollar value.

Table 19: Fixed and Variable costs of new SPS plant (Pina et al., 2008)

Seawater Pumped storage	Investment costs	Fixed (O&M) costs
2008 cost estimate	2000 €/kW	46 €/kW
*1€ = 1.47 US Dollar in 2008 (Best, 2021)	2940 $/kW	67.62 $/kW
2020 cost estimate * 1.00 US Dollars of 2008 are worth 1.21 US Dollars of 2020 (Casais, 2021)	3557.4 $/kW	81.82 $/kW

The proposed SPS plant possesses a power capacity of 36.3 MW and energy storage capacity of 181.5 MWh. Therefore, the cost of the plant is calculated as follows:

- $\text{Investement costs} = 3557.4\ \left(\frac{\$}{\text{kW}}\right) \times 36.3(\text{MW}) \times 1000\ \left(\frac{\text{KW}}{\text{MW}}\right)$

  $= \$129.13\ \text{million}$

- $\text{Fixed (O\&M)costs} = 81.82\ \left(\frac{\$}{\text{kW}}\right) \times 36.3(\text{MW}) \times 1000\ \left(\frac{\text{KW}}{\text{MW}}\right)$

  $= \$2.97\ \text{million}$

b. SPS plant cost estimate based on MEI costing model (Hearps et al., 2014)

i. MEI reservoir cost model

The plant reservoir is assumed to be of line earth-embankment dam type, illustrated in Figure 35.

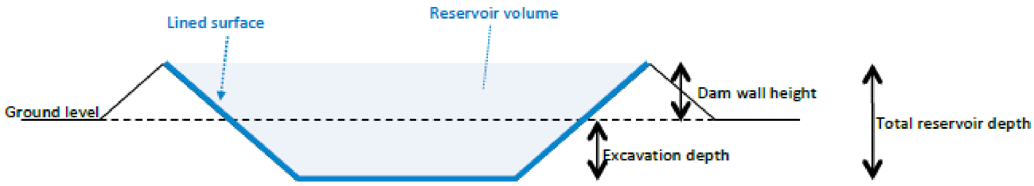


Figure 35: Cross-sectional design of earth embankment type reservoir for MEI costing model (Hearps et al., 2014).

Hearps et al. (2014) in MEI cost model assumed a cost of A$ [2] 60/m^2 for lining the inner reservoir surface and a A$ 17/m^3 of material excavated for the excavation cost. The following empirical formula, equation 3, was derived to estimate the cost of the reservoir, C_R , it reflects the excavation and lining costs (Hearps et al., 2014).

Equation 3: MEI reservoir cost empirical equation (Hearps et al., 2014)

$$C_R = 141 \times V^{0.818}$$

Where: C_R is reservoir cost in A$, and V = reservoir volume (m^3)

The formula is as a function of the reservoir volume. This was justified by MEI research that the reservoir cost is insensitive to the depth, beyond 30 meters depth, because the cost of lining is the dominant cost factor with the increasing reservoir volume (Hearps et al., 2014). According to Figure 36, for a reservoir volume of 50,000,000 m^3 the cost curve is approximately flat, the cost slightly changes with decreasing depth. Therefore, since the suggested plant reservoir volume is 415,641.52 m^3 this empirical formula can be used to estimate the reservoir cost.

[2] Australian dollar: 1 A$ = 0.9021 USD, average exchange rate in 2014 (Australian Dollar to US Dollar Spot Exchange Rates for 2014, 2021)

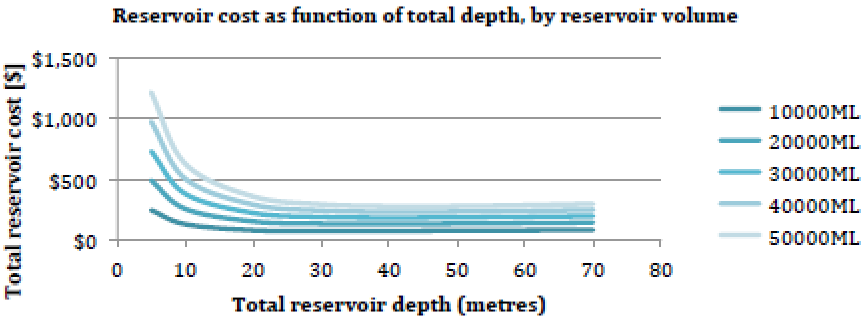


Figure 36: Earthworks plus lining costs in A$ for an earth-embarkment type reservoir as a function of depth (m) and reservoir volume (ML = 1000 m3), MEI (Hearps et al., 2014).

The cost of reservoir finishing needs to be added to this cost in case of seawater pump storage (Hearps et al., 2014). These costs are the cost of drainage and pumping layer deployed in the Okinawa Japan SPS plant. Therefore, a 50% premium needs to be added to the initial excavation and lining cost (Black & Veatch, 2012).

Therefore, the reservoir cost of the proposed SPS plant is:

$C_R = 1.5 \times 141 \times 415641.52^{0.818} = \text{A\$ } 8.345 \text{ million} = \$7.53 \text{ million}$

In terms of current dollar value, where 1.00 US Dollar of 2014 is worth 1.10 US Dollar of 2020 (Casais, 2021):

$$C_R = \$7.53 \text{ million } \times 1.1 = \$8.283 \text{ million}$$

ii. MEI piping/ tunneling cost assumptions

Based on the site topography, the upper and lower reservoirs of the pump storage plant can be connected by either tunneled pipelines or by above-ground piping and penstocks. The latter is a cheaper option. Hearps et al. (2014) based on references assumed a cost of A$ 100 million/km of horizontal reservoir separation for tunneled pipelines, and a cost of A$ 10 million/km of horizontal reservoir separation for above ground piping.

Figure 37 represents the ground elevation profile of the line connecting the reservoir and seashore. It is assumed that from the upper reservoir and for a distance of 0.349 km tunneled pipelines will be installed and from this point, which is highlighted in a red arrow in figure, and for a distance of 0.3 km, surface piping will run to meet the seashore.

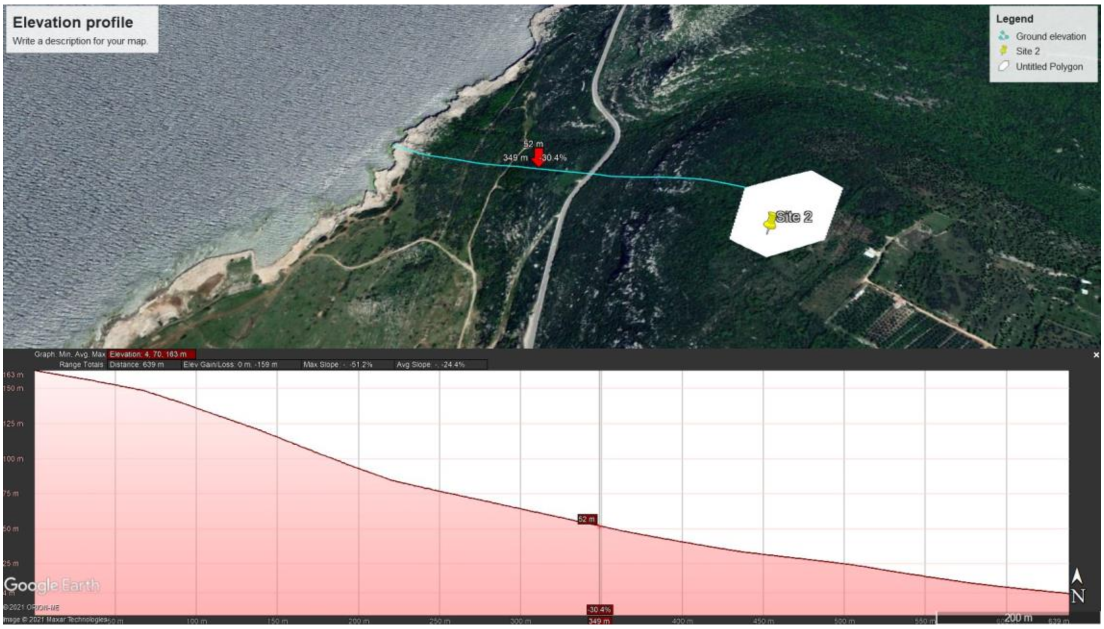


Figure 37: Ground surface elevation profile between SPS reservoir and seashore (Google Earth, 2021)

The cost of tunneling and piping, C_P , is calculated as follows:

$$C_P = 0.349 \times 100 + 0.3 \times 10 = 37.9 \text{ A\$ million} = \$34.19 \text{ million}$$

In terms of 2020 dollar value:

$$C_P = 34.19 \text{ \$ million} \times 1.1 = \$37.61 \text{ million}$$

iii. MEI electrical and mechanical components cost model

The MEI empirical formula for the electrical and mechanical costs, C_{em}, is:

Equation 4: MEI electrical and mechanical components costs empirical equation (Hearps et al., 2014).

$$C_{em} = 3.3657 \times P^{0.891} \times H^{-0.336}$$

Where: C_{em} is the electrical and mechanical costs in US$ million, P is power in (MW), and H is net head in (m).

The electrical and mechanical material of the seawater pump storage plant should be made of austenitic stainless steel to prevent corrosion from seawater. Since no information is available about the cost of austenitic steel materials a 50% premium is applied on costs of electrical and mechanical equipment (Hearps et al., 2014).

The proposed SPS plant possesses a power capacity of 36.3 MW and a head of 173.71 m. Therefore, the electrical and mechanical costs is:

$$C_{em} = 1.5 \times 3.3657 \times 36.3^{0.891} \times 173.71^{-0.336} = \$21.9 \text{ million}$$

In terms of current dollar value:

$$C_{em} = \$21.9 \text{ million} \times 1.1 = \$24.09 \text{ million}$$

iv. Direct costs

The direct costs are considered as the total of reservoir, tunneling and piping, and electrical and mechanical costs (Hearps et al., 2014).

$$\text{Direct costs} = C_R + C_P + C_{em} = 8.283 + 37.61 + 24.09 = \$69.983 \text{ million}$$

v. Indirect costs

The indirect costs that should be added to the direct cost are the engineering procurement and management, the contingency and the owner's costs that accounts for 10%, 20% and 20% of direct costs respectively (Hearps et al., 2014).

$$\text{Indirect costs} = 0.1 \times 69.983 + 0.2 \times 69.983 + 0.2 \times 69.983 = \$34.9915 \text{ million}$$

vi. The proposed SPS plant total cost based on MEI costing model

The total cost of the proposed SPS plant is the sum of the direct and indirect costs and it is equal to $104.9745 million.

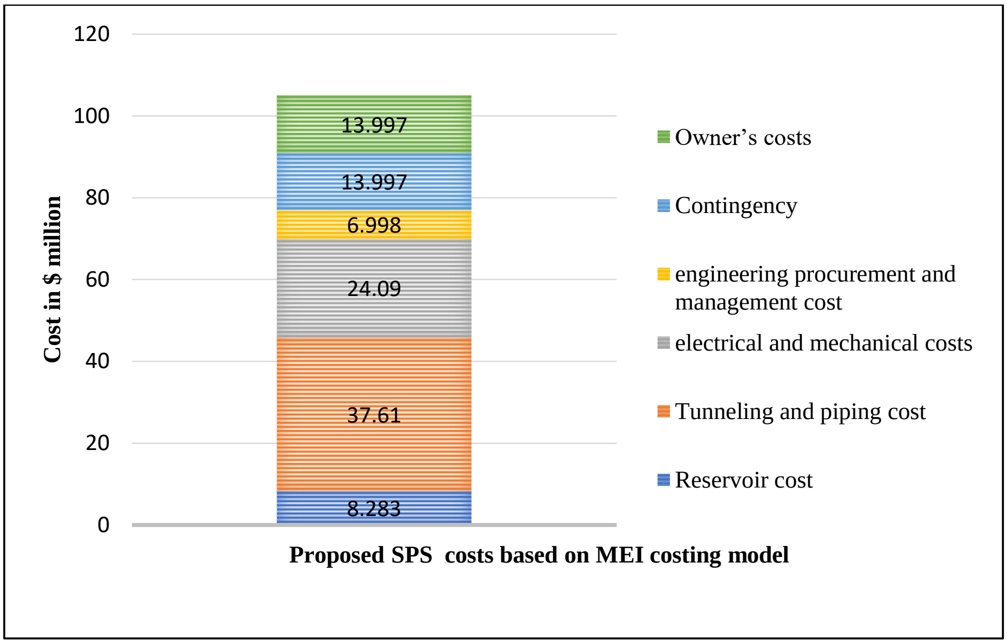


Figure 38: Histogram of the proposed SPS direct and indirect costs based on MEI costing model.

c. *Proposed SPS plant investment costs*

The cost of the proposed plant is assumed to be the average cost value of the two cost estimates derived from Pina et al. (2008) and MEI costing method (Hearps et al., 2014). Therefore, the investment cost of the SPS plant is $117.06 million.

The cost estimation can be more accurate and improved after having the full design and engineering drawings of the proposed SPS plant, and also by estimating the costs based on the Lebanese market.

2. *Operation and maintenance cost*

The annual average operation and maintenance costs, O&M costs, of pumped hydroelectric storage is around 1 to 2% of the investment cost (Connolly, 2010). Taking a midpoint value of 1.5%, and using the MEI costing model, the O&M costs of the proposed SPS plant is $1.575 million per year. The O&M costs estimated from Pina et al. (2008) is $2.97 million. Therefore, taking the average value of these two O&M costs estimates the O&M of the proposed SPS plant is $2.27 million.

B. SPS plant yearly revenue estimation

The yearly plant revenue is the given by the surplus money obtained from the difference between the value of energy generated sold and energy purchased for pumping.

1. Present EDL tariffs by customer category/ block

According to EDL the current electricity tariff structure is as follows, for:

- Residential and commercial: 2.3 – 13.3 US cent/kWh
- Agriculture and Industrial: 7.7 US cent/kWh
- Government and Public Admin: 7.7 US cent/kWh

2. Annual pumping consumption

The energy required to pump seawater up during the off-peak hours is obtained using the following formula:

Equation 5: Hydraulic pump power equation (Pump power calculator, 2003).

$$P_h = \frac{q \times \rho \times g \times h}{3.6 \times 10^6}$$

Where:

P_h (kW) = hydraulic power (kW)
q = flow (m^3/h)
ρ = density of seawater (1025 kg/m^3)
g = acceleration of gravity (9.81 m/s^2)
h = differential head (m)

For the pumping mode, the flow is taken as 20.2 m^3/s (Oshima et al., 1999).

Therefore, the hydraulic power is 35,283.29 kW.

$$P_h = \frac{(20.2 \times 3600) \times 1025 \times 9.81 \times 173.71}{3.6 \times 10^6} = 35{,}283.29 \text{ kW}$$

The reservoir volume is 415,641.52 m^3, thus the pump needs to operate for 5.8 hours daily to fully fill the upper reservoir and the daily pumping power is 204,643.1 kWh.

$$\text{Daily pumping operation hours} = \frac{V(m^3)}{q(\frac{m^3}{h})} = \frac{415641.52}{20.2 \times 3600} = 5.8 \text{ hours}$$

Assuming the average annual operation days is 300 days (Geadah, 2009), the annual pumping consumption is 61,392,930 kWh.

3. Annual generation production

The proposed SPS plant has a capacity of 181.5 MWh per day. Assuming the average annual operation days is 300 days (Geadah, 2009), the annual generation production is 54,300,000 kWh.

4. Annual pumping cost, generation sales, and gross profit

ESMAP (2020) recommended a tariff design for the Lebanese electricity sector to improve the cost recovery in the short term. Since EDL earns 62% of its revenues from the last customer block, which uses more than 500 MWh, one option was to target the high consumption blocks for applying tariff increase (ESMAP, 2020). ESMAP (2020) suggested six tariff adjustment scenarios, the last two were: (i) to increase all customers tariffs by 50%, i.e. 0.13 $/kWh, except for the first two blocks, to increase the total EDL revenues billed by 39.3%, and (ii) to increase all customers tariffs by 95%, i.e. 0.16 $/kWh, except for the first two blocks, to increase the total EDL revenues billed by 74%. The first two blocks are the customers that use less than 100 or 300 MWh (ESMAP, 2020).

EDL applies the Time-Of-Use tariff to the high demand customers, that use more than 100 KW. The tariff rate varies between night, day, and peak hours from 0.05 $/kWh and reaches a maximum of 0.21 $/kWh (ESMAP, 2020).

Therefore, three scenarios about different pricing level of peak energy sold are studied. Table 20 represents the assumed off-peak pumping and peak generation costs per kWh of the proposed SPS plant.

Table 20: Assumed pumped-storage costs.

Off-peak pumping costs	Peak Generation costs, price per kwh sold		
	Scenario 1	Scenario 2	Scenario 3
7 US cent/kWh	13 US cent/kWh	16 US cent/kWh	21 US cent/kWh

The annual pumping cost, generation sales, and gross profit under the three scenarios are represented in Table 21.

Table 21: Annual pumping cost, generation sales and gross profit.

	Scenario 1	Scenario 2	Scenario 3
Annual pumping cost ($ million)	4.3	4.3	4.3
Annual generation sales ($ million)	7.06	8.69	11.41
Annual gross profit ($ million)	2.76	4.39	7.11

C. Financial Feasibility

The lifespan of electro-mechanical equipment for pumped hydro storage plant extends between 40 and 50 years (Pandey et al., 2016). For this study, the useful life of SPS plant is assumed as 40 years.

In context of climate change and societies investments to limit its impacts, the social discount rate is applied to these types of public investments. In Britain, the social discount rate for the public sector is 3.5% (H.M. Treasury, 2018).

IRENA (2020) use a discount factor varying from 7%, in case of good market conditions, and reaches 13%, in case of poor market conditions. These discount rates were used to estimate the levelized cost of electricity in Lebanon. Moreover, UNDP (2020) assumed that a discount factor of 12% is a reasonable value to be applied for the current developments in Lebanon.

The net present value of the project was computed for three discount rates values, 3.5%, 7%, and 12%, and under the three scenarios of price of electricity sold mentioned in Table 21.

As shown in Figure 39, for a discount factor of 3.5%, the project will break-even under scenario 2 and 3 at year 30 and year 17 respectively. However, under scenario 1 the project will not break even during the lifespan of the plant.

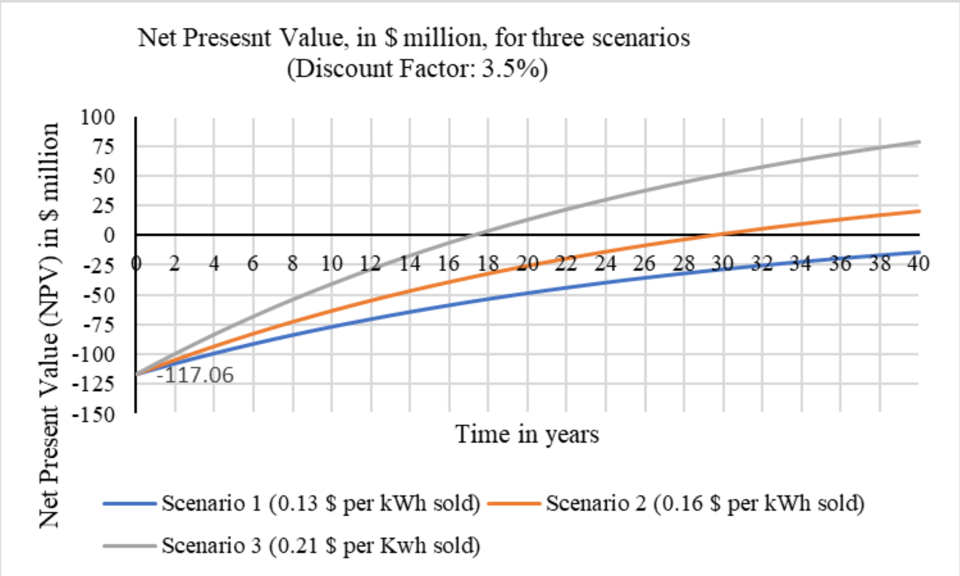


Figure 39: Net Present Value, in $ million, for the three scenarios, for a discount rate of 3.5%.

As shown in Figure 40, for a discount factor of 7%, the project will break-even under scenario 3 at year 34. However, under scenario 1 and 2 the project will not break even during the lifespan of the plant.

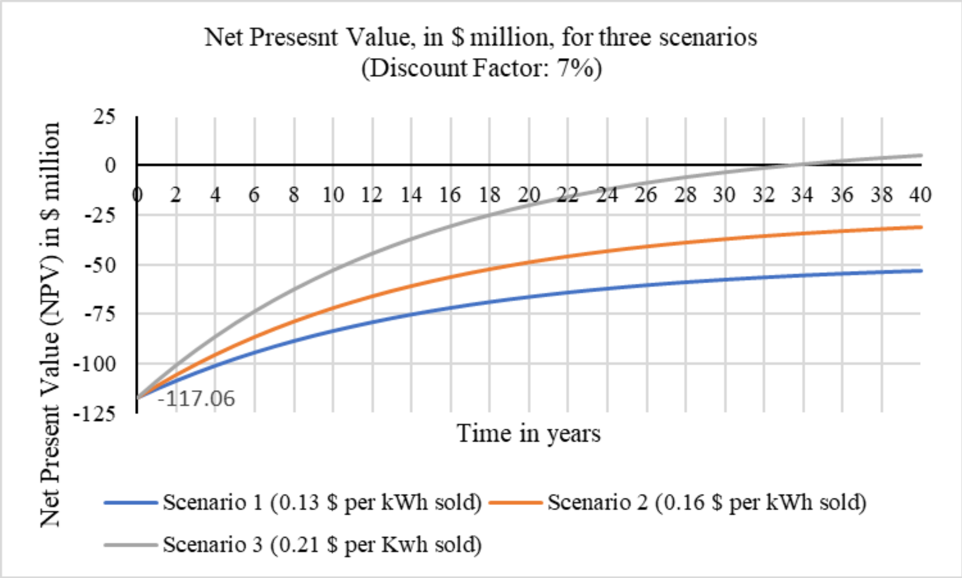


Figure 40: Net Present Value, in $ million, for the three scenarios, for a discount rate of 7%.

As shown in Figure 41, for a discount factor of 12%, under scenario 1, 2 and 3 the project will not break even during the lifespan of the plant.

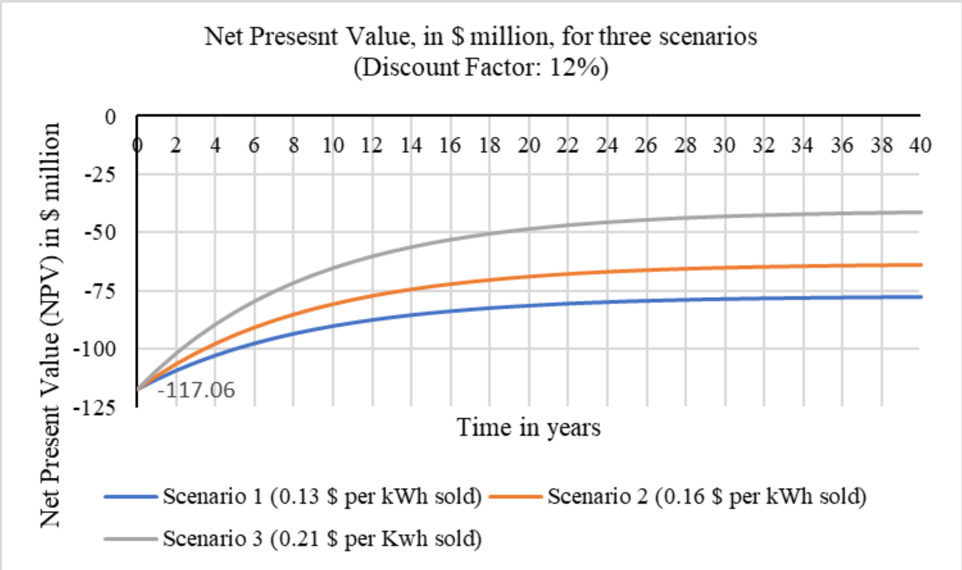


Figure 41: Net Present Value, in $ million, for the three scenarios, for a discount rate of 12%.

CHAPTER VII

CONCLUSION

Seawater pumped storage (SPS), which is a modified form of pumped hydroelectric storage, has the potential to reduce the problem of peak demand and enhance the penetration of intermittent renewable energy sources in the Lebanese electricity sector. This research has assessed the seawater pumped storage potential in Lebanon. A Geographic Information System (GIS) based approach was used to preliminary locate suitable artificial upper reservoir sites of an SPS plant near the Lebanese coastline. First, based on a literature review, several site selection factors for the SPS plants were identified. The parameters found were categorized into techno-economic (length to head ratio, elevation head, and slope), social/environmental (land use and land cove, and distance from urban and archeological sites), and infrastructure factors (power grid proximity, and road network proximity). These factors were given different weights based on their relevance to the SPS site selection. The results of the search revealed the presence of two potential SPS upper reservoir sites, both located in Ras Chekkaa, Lebanon North Governorate. The elevation above sea level is 170.7 m for Site 1, and 173.71 m for Site 2. The sensitivity analysis of the GIS model showed that the model is insensitive to changing the weights of the site selection factors.

The power capacity equation (Connolly, 2010) was used to determine the power generated from the SPS plant based on the site elevation. Therefore, Site 1 and Site 2 possess a potential power capacity of 35.7 MW and 36.3 MW, respectively, which is about 40% of the 93 MW average difference in electricity demand during peak hours in Lebanon. The storage capacity equation (Connolly, 2020) and daily operation hours were then used to determine the reservoir volume, which represents the volume of seawater that needs to be filled daily. Referring to the daily electricity load curve of Lebanon (EDL, 2015), the SPS plant should produce daily power during the five peak hours, which occur between hour 17 and 22. Hence, the daily storage capacity and the reservoir volume for Site 1 and Site 2 are 178.5 MWh and 415,979.394 m3, and 181.5 MWh and 415,641.52 m3, respectively.

The two potential sites were further studied in terms of environmental/social, land ownership, geotechnical and water table vulnerability aspects. The sites were narrowed down to one site. Site 1 was discarded from the study since its area intersects with Deir El Nouriyeh cliffs of the Ras Chekaa wetland. A study by Faour et al. (2016) investigated the Cliffs of Ras Chekkaa along the northern coast, Mazra'at Hanouch, as a wetland area and concluded that the site poorly meets the wetland criteria. Therefore, access to the sea from Site 2 can be guaranteed. The land of Site 2 is privately owned by the convent of Saidet El Nouriyeh (Ramsar, 2012). The geological condition of Site 2 was then assessed. Three major geological rock formations made Ras Chekkaa stratigraphy: (i) Quaternary deposits, (ii) Miocene Marly Limestone, and (ii) Senonian Marl (Faour et al., 2016). The soil parameters used in the study of Sadek & Hamad (2007) to assess the structural safety of the Chekka tunnels were also used in this study. Since the groundwater depth in Chekka varies between 10 and 35 m (UNDP & MoEW, 2014), the reservoir was designed to have a maximum excavation of 8 m. The reservoir shape is hexagonal with a surface area of 88,794.34 m2.

The settlement of the land subject to the load of the filled reservoir was assessed using Settle3D software. The results of the analysis showed that the geological condition of Site 2 is suitable for the construction of the proposed SPS plant. The design, materials and environmental measures of the Okinawa Japan SPS plant, the only SPS plant implemented worldwide, were reviewed. The reservoir needs to be lined with ethylene propylene diene monomer (EPDM) rubber sheet and a drainage layer with sensors should be constructed to prevent seawater leakage. Moreover, to prevent corrosion from seawater the fiberglass-reinforced plastic (FRP) pipes should be used, and the hydroelectric equipment should be made of austenitic stainless-steel material. In addition, several environmental measures must be implemented to conserve the land and sea during the construction and the operation of the plant.

Based on (Pandey et al., 2016), the lifespan of the proposed plant was assumed as 40 years. The estimated SPS plant investment cost is $117.06 million with an annual average operation and maintenance costs of $2.27 million. The plant's average operation days was set as 300 days and the pumping cost was set as 0.07 $/kWh. The financial feasibility of the plant was studied over its lifetime for three different discount rate values (3.5%, 7%, and 12%) and for three different prices of electricity sold (0.13, 0.16, and 0.21 $/kWh). The results showed that for a discount factor of 3.5% or less, the minimum price of electricity sold by the plant must be 0.16 $/kWh for the project to make economic sense. Moreover, for a discount factor of 7% or less, the power sold by the SPS plant must be at least 0.21$/kWh for the project to be financially feasible. However, for a discount rate of 12%, which according to UNDP (2020) this value reflects the current investment borrowing conditions in Lebanon, the SPS project is not feasible for a price of 0.21 $/kWh or less for electricity sold.

For future research, a more dynamic modeling of the Lebanese grid needs to be made in order to assess the implications of the integration of the proposed seawater pumped storage plant in the Lebanese electricity mix. This modeling would help indicate which exact peak load power plant will be displaced with the use of the proposed SPS plant. Moreover, due to the difference in energy mix during the pumping and generating electricity modes, the environmental benefits of the proposed plant need to be studied. This study could be done by assessing the footprint of the energy mix during the plant's pumping and generating modes.

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