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Design of a pumped Hydroelectric Energy Storage (PHES) system for Jordan

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التوقيـع:

التاريـخ: ٢٣/ ٥/ ٢٠١٧

DESIGN OF A PUMPED HYDROELECTRIC ENERGY STORAGE (PHES) SYSTEM FOR JORDAN

By

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This Thesis was Submitted in Partial Fullfillment of the Requirements for the Master's Degree of Renewable Energy.

School of Graduate Studies

The University of Jordan

April 2017

COMMITTEE DECISION

This Thesis (Design of a Pumped Hydroelectric Energy Storage (PHES) system for Jordan) was successfully defended and approved on 2/5/2017.

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DEDICATION

This work is dedicated to my parents and my friends…….

ACKNOWLEDGEMENT

I would first like to thank my supervisor Dr. Salih Akour for being generous with his precious time to guide me through my master thesis. He consistently allowed this thesis to be my own work. The door to his office was always open whenever I ran into a trouble spot or had a question about my research. I also would like to acknowledge the Mechanical department at Jordan University.

I would also like to thank the PLEXOS analysts in the supporting department of energy exemplar who trained me to master PLEXOS software. Without their valuable assistance, this work could not have been successfully accomplished.

I would also like to acknowledge every person who works in the Jordan national electric company and the authority of Jordan valley that provided me all needed technical data.

Finally, I must express my very profound gratitude to my parents to my friends for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

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LIST OF ABBREVIATIONS

Pumped Hydroelectric Energy Storage	:	PHES
National Electric Power Company	:	NEPCO
Jordan Valley Authority	:	JVA
Electrical Energy Storage	:	EES
Roller Compacted Concrete	:	RCC
Mixed Integer Programming	:	MIP
Water Pump Station	:	WPS
Million Cubic Meter	:	MCM
Million British Thermal Unit	:	MMBTU

LIST OF NOMENCLATURES

P_P	:	Rated Pump Power
Q_P	:	Rated volume flow rate
η_P	:	Pump efficiency
g	:	Acceleration of gravity $(9.8\, m/s^2)$.
ρ	:	Density of water $(1000\, Kg/m^3)$.
h	:	Head
V_R	:	Volume of the upper reservoir
T	:	Rated pumping time in second
η	:	Turnaround efficiency of PHES
η_p	:	Pump efficiency
η_g	:	Generation efficiency
Ns	:	Specific speed
N	:	Runner speed
A	:	Section area of the pipe
v	:	Velocity in the pipe
D	:	Pipe diameter
H_d	:	Dynamic head
K	:	Loss coefficient
K_{Pipe}	:	Pipe Loss coefficient
$K_{Fitting}$	:	Fitting Loss coefficient
f	:	Friction coefficient
L	:	Pipe length

ε	:	Roughness factor
Re	:	Reynold number
υ	:	Kinematic viscosity
H_s	:	Static head
$L_{Upper.r}$	:	Water level in upper reservoir
$L_{Lower.r}$	:	Water level in lower reservoir

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ABSTRACT

Renewable energy sources particularly wind energy is becoming immensely popular throughout the world. Jordan is one of the countries that are interested in increasing the integration level of the wind energy on the national electrical grid. The main drawback of wind power is its inherent variability and uncertainty of source making wind energy a difficult resource to dispatch. A Pumped Hydroelectric Energy Storage (PHES) system is considered to be an attractive alternative solution for load balancing and energy storage mainly with wind farms. The current research utilizes the existing dams in Jordan as lower basin and provides candidate locations for upper pumped storage basins in the vicinity of these dam without affecting their functionality. These upper basins are semi-natural basins with least amount of construction, i.e. relatively least cost as shown in the economic analysis of implementing such project.

All power systems of both conventional and renewable energy in Jordan are modeled using PLEXOS software package. The optimization technique of Mixed Integer Programing is utilized to achieve optimum solution for wind energy variability and uncertainty. The power model is designed by using the actual characteristics of all power generating units in Jordan. Real demand load data obtained from the National Power Company are implemented in the design model so the study provides real life solution for the variability of renewable energy sources mainly Wind Energy. Wind speed is obtained for one year for Al-Tafila heights and implemented in the design model. Analysis is carried out for power systems with and without PHES to show the improvements that are achieved by using such storage system.

A location survey of the candidate sites in Jordan is conducted where the PHES can be installed and operated in an efficient manner. Ten locations have been analyzed deeply in the location survey. The results show that six of them are successful candidates and appropriate locations to install PHES system since they pass all PHES design requirements. Al-Tannur dam has been selected as case study for designing PHES system for Jordan. The analysis of practical power model is carried in different scenarios; with and without inclusion of PHES unit. The positive effect on the behavior of the power system when the PHES is included is clearly observed, wind integration level has been increased and dispatched on demand. The generation in peak demand by the inefficient costly units is reduced so the total generation cost has been diminished.

Chapter One

Introduction

1.1 Renewable Energy Overview

The renewable energy sources are steadily expanding. Many countries around the world have started to install facilities that use renewable energy sources for power generation. The importance of renewable energy sources comes together with climate change challenges associated with the excessive use of fossil fuels. There are also three main motivators that accelerate the development of renewable energy systems: energy security, economic effects, and carbon dioxide emissions restriction. The developments in technology have allowed nations to produce renewable energy more price effectively

Solar energy has a significant potential and its utilization is expanding extremely fast. It can benefit to prevent the greenhouse gasses that threaten irreversible environmental change for the world. Solar energy currently contributes a little to reduce emissions. However, it will certainly have a significant motivation in climate-friendly scenarios in the next years. Solar energy, continues to be one of the fastest-growing energy markets over the past few years. It is supposed to get competitiveness a huge scale within ten years

Wind energy, is known as the most feasible as well as the most reliable among the renewable energy systems after hydropower. Recent times have experienced an acceleration in wind energy technology expansion and a rise in investment projects. Therefore, led to increase the number of experts, and achieve a significant working experience in this field all over the world.

Wind power is make use of air movement by using wind turbines to operate an electrical generator for electricity generation. Wind energy, as opposed to fossil fuels, is sufficient, sustainable, extensively distributed, clean, releases no greenhouse gas emissions while operating, requires no water, and needs small area. The cumulative effects on the natural environment are much less problematic than those of nonrenewable power supplies.

Wind farms comprise of some individual wind turbines which are usually hooked up to the electric utility transmission network. It delivers variable power which is very steady from year to year but has a considerable variation over quite short timescales which will affect the performance of the power grid. Therefore, there is an urgent need to include storage systems in the power system, which aid in regulating the movement of electricity in the electric grid.

1.2 Renewable Energy in Jordan

Jordan has an excellent potential of renewable energy such as wind and solar**.** So it is one of the countries that interested in expanding the utilization of renewable energy sector. Jordan is located within the sunbelt where the intensity of direct solar radiation is about (5-7)kWh/m2. Therefore, there is a massive opportunity to use this energy (Al zou'bi, 2010).

Now, there are several projects have finished construction. Two solar PV projects with total capacity of 5 MW at Azraq in cooperation with the Spanish government. Twelve PV projects agreements of the solar cell to generate electricity with a total capacity of 200 MW mostly in Ma'an and solar Pv project at Quera/Aqba 65-75 MW (Sahawneh, 2015).

Also, Jordan is rich in wind resources, Wind speed reaching between 7.5 to 10.0 m/s in some places as shown in Figure 1.1. So it is one of the countries that are interested in wind energy since 1996. At this time there are four wind power plants hooked up to the national grid, that located at Ibrahimyah, Hoffa, Tafila, and Ma'an.

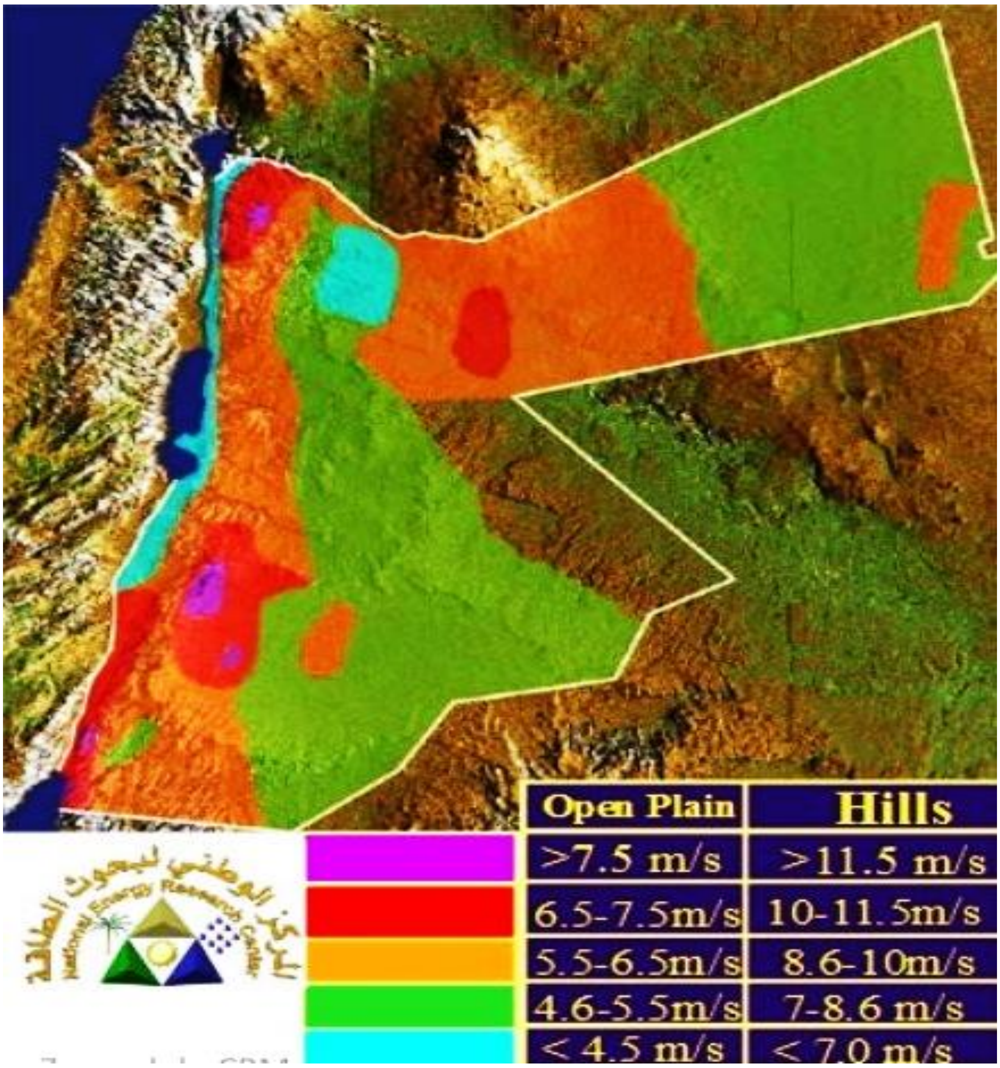

Figure 1.1: Wind map in Jordan (Ministry of Energy and Mineral Resources,2012)

Ibrahimyah plant is located close to 80 km north of Amman, consists of 4 wind turbines with a capacity 0.08 MW for each turbine. The Hoffa plant is located nearly 92 km north of Amman, consists of 5 wind turbines with a capacity 0 .225 MW for each turbine. Tafila Wind Farm is located in Tafila Governorate in the southwest of Jordan; it is the first large-scale wind power plant, it has started it's electrical energy production with a capacity of 117 MW in 2015. Ma’an Wind Park has been hooked up to the national grid with a capacity of 80 MW in 2016.

These wind stations are just the beginning not the last, so a target of 10% of renewable energy input to the energy mix by 2020 is set in the national energy strategy. It aims mainly to increase the rated power generated from the wind to 1200 MW and 600 MW of solar. Table (1.1) shows the recent and future plan of installing wind stations in Jordan (Sahawneh, 2015).

Table 1.1: Future plan of wind stations (Sahawneh, 2015)

Station	Capacity MW						
	year						
Wind park	2015	2016	2017	2018	2019	2020	Total
Tafila	117						117
Ma'an		80					80
Various			100	300	300	300	1000
Total							1197

The most critical weakness of wind power is its natural variability, and also the uncertainty of source. That is why a massive range integration of wind is a danger to the stability and reliability of electric grids hosting wind energy conversion systems (Namgyel, 2012).

It is clear that wind energy sector will continue to expand in Jordan. Therefore, fail to use proper energy storage system by the electricity distribution company, will lead to lack of balance between the electricity generated by wind farms and the rate of energy demand.

Pumped Hydroelectric Energy Storage (PHES) systems are considered an attractive alternative solution for load balancing and energy storage. They can supply ancillary services at high ramp rates, and they can additionally provide benefits from intraday energy price variation by releasing the energy at high demand periods, and using the energy at off-peak periods to pump water into a high potential energy reservoir (Namgyel, 2012).

1.3 Problem statement

With persistently increasing fuel prices and growing environmental concerns, the energy from renewable resources, particularly wind energy is becoming immensely popular throughout the world.

Jordan is one of the countries that are interested in wind power, in 2015, the first large scale wind power plant- Tafila wind farm has started its electrical energy production with a capacity of 117 MW. In the near future Ma'an Wind Farm will be hooked up to the national grid with a capacity of 80 MW. Through the upcoming years other farms will be installed and connected to the national grid.

The main drawback of wind power is its uncertainty of source making wind energy a difficult resource to dispatch. For this reason, large scale integration of wind is a threat to the stability of utility grids. Utility grid should consider this main issue to match the energy produced by the wind farms to the energy demand. The challenge is to find a way to make energy created by wind resources available on demand.

In Jordan, National Electric Power Company (NEPCO) control the power generation from the power plants. If the wind integration is increased it will experience difficulty on controlling power flow through the system which highly motivate the adoption of PHES System integration. Properly designed PHES if integrated into the Jordan power system, can offer maximum flexibility to resolve the problem of wind integration.

1.4 The main objectives

1. Site Analysis, which includes geographic data collection and proper site selection.
2. Design a PHES system to avoid the loss of energy generated by the wind farms at off-peak load.
3. Regulate and control of the energy generated from wind farms in Jordan.

1.5 Methodology

This study focuses on the impact of inclusion PHES in the power system along with the increasing of wind power integration level in Jordan. Three main aspects related to energy storage system will be studied which are: conducting a location survey to examine the candidate sites for PHES installation in Jordan, designing of PHES system station, modeling a practical power system for Jordan which includes all thermal generating units, wind farms and PHES unit.

In the location survey a water balance for each dam has to be done and all data that is needed will be collected from Jordan Valley Authority (JVA). All the power system data that is needed to accomplish this study will be collected from NEPCO.

An academic version of PLEXOS for Power Systems, will be used to model the practical power system which is a simulation software for energy market analysis.

1.6 Thesis layout

This thesis is structured as follows: Chapter one presents the background of the study, the problem statement and its significance, methodology and the main objectives of the study. Chapter two gives published literature of different topics relevant to the study. Chapter three provides a location survey study of the candidate sites. Chapter four represents the procedure to design PHES. Chapter five provides the information about the power modeling. Chapter six discuss the results after run the power model. Chapter seven provide an economic study for the PHES. Chapter eight summarizes the conclusions and provides some recommendations.

Chapter Two

Literature Review

2.1 The History of PHES

In the last decade, interest in a large Electrical Energy Storage (EES) systems has expanded significantly as a good potential strategy to many of the issues related to renewable energy systems. One of the most significant challenges of many low-carbon generation systems is usually that they lack the same level of load-following flexibility as compared with a conventional fossil fuel power generation. This applies to renewable generation technologies which are weather conditions dependent. For instance, the wind and solar primary energy resources are varied, often unexpected.

The limited ability of the wind and solar systems to load- follow, is among the most significant problems that bulk EES aims to handle. Many research studies have considered the energy storage as an essential method of contributing the flexibility that is necessary to integrate massive proportions of renewable energy in electricity networks. Through a report that is done by (Denholm, Ela, Kirby, & Milligan, 2010), for the National Renewable Energy Laboratory, USA concludes that high penetrations of variable generation will extend the interest on all flexibility options, which includes energy storage systems. (Eyer & Corey, 2010), also summarize that renewable energy integration is among the major drivers for energy storage as well as (Beaudin, Zareipour, Schellenberglabe, & Rosehart, 2010), conclude that large-scale renewables integration would be an extra difficult challenge without energy storage. (Cochran, Bird, Heeter, & Arent, 2012), review the most suitable methods for integrating variable renewable generation to the grid, and conclude that there is no one size that matches all energy demand. Therefore, that will encourage the development of energy storage systems. Although it is accepted that smaller percentages of renewable generation can integrated into many electrical power systems without very considerable operational variations (Gross et al., 2007).

PHES also offers various advantages throughout the power supply chain, and some research studies have talked about these (Barbour, Wilson, Radcliffe, Ding, & Li, 2016), They involve:

- Allowing greater deployment of low-carbon generation
- Facilitating a time of use energy management
- Increasing reliability for end-users
- Minimizing the fluctuation of electricity prices
- Improving system reliability
- Maximizing system flexibility
- Reducing the require for transmission upgrades/new transmission infrastructure
- Reducing overall pollutant emissions.

As shown in Figures 2.1 PHES stores electrical energy by elevating water to upper reservoir. The charging process converts electrical energy into mechanical energy and eventually into gravitational potential energy, by using the power to pump water from a lower reservoir to a higher reservoir. The discharging process is the reverse; it converts gravitational potential energy into mechanical energy and then to electrical energy by allowing water to flow down from the higher reservoir to the lower reservoir, driving a turbine that is attached to an electrical generator. Table 1 gives some of the typical technical characteristics of PHES plants (Chen et al., 2009).

At a country level, Japan has the largest installed capacity of PHES at ~25 GW (Deane, , Gallach, & McKeogh, 2010), which represents over 8.5% of its installed electricity generating capacity. China has the second largest capacity of PHES followed by the USA. However, PHES constitutes only 1.8% and 1.9% respectively of their total installed electric generation capacity. Table 2 shows some countries with the largest installed PHES capacities.

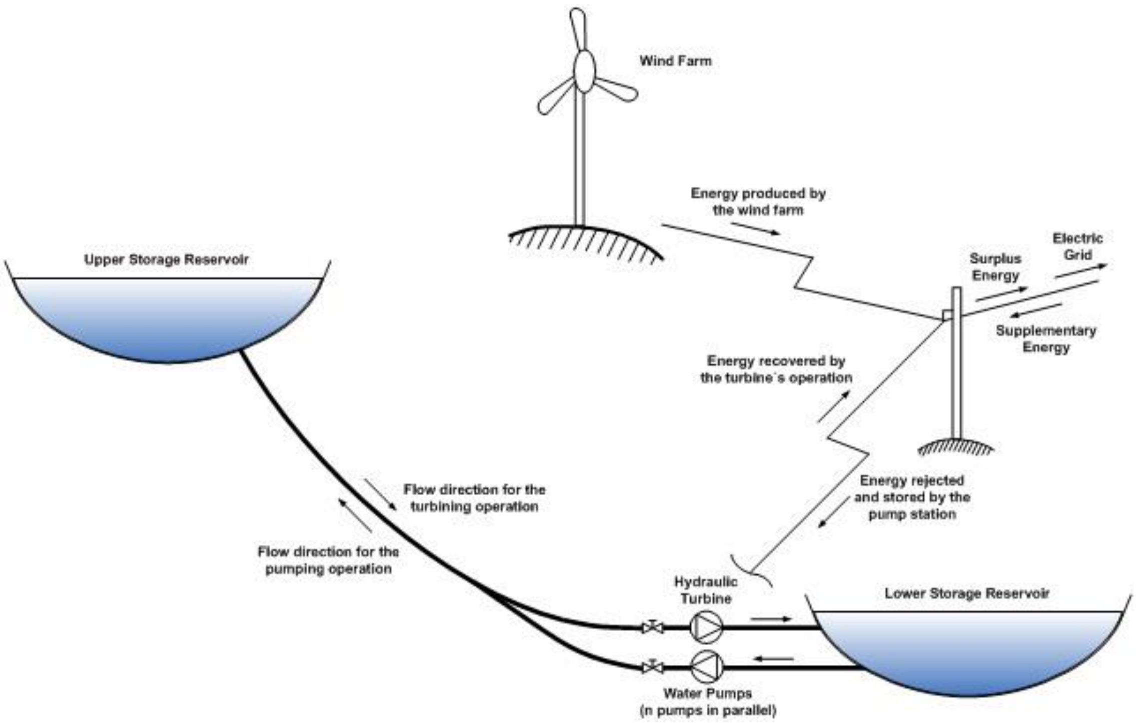

Figure 2.1: PHES operation (Energy Storage Technologies for Electric Applications, 2014)

Table 2.1: Technical characteristics of PHES (Beaudin et al., 2010)

Power	10-4000 MW
Discharge duration at rated power	1-24 + h
Round-trip efficiency	70-85%
Self-discharge	Generally negligible
Response time	Min
Power capital cost	2000-4300 $/kW
Energy Capital cost	5-100 $/kWh
Lifetime	40-60+years
Suitable storage duration	Hours - Days

Table 2.2: Installed PHES capacity by country and current (2014) capacity under construction. (Deane et al., 2010; Yang & Jackson, 2011)

Country	Installed PHS capacity (GW)	Under construction (GW)	PHES power capacity as a % of installed electrical generating capacity
Japan	24.5	3.3	8.5
China	22.6	11.6	1.8
USA	20.5	-	1.9
Italy	7.1	-	5.7
Spain	6.8	-	6.6
Germany	6.3	-	3.5
France	5.8	-	4.4
India	5.0	1.7	2.2
Austria	4.8	0.2	21
Great Britain	2.7	-	3.0
Switzerland	2.5	2.1	12
Portugal	1.1	1.5	6.1

2.2 Historical development of PHES

2.2.1 Europe

Figure 2.2 illustrates that The European countries have the most PHES capacity, and that over 80% of it was commissioned between 1960 and 1990. The largest number of the schemes are situated in the mountainous regions of Germany, Italy, France, Spain and Switzerland. Although in a number of nations, development was in parallel with significant increases in nuclear capacity. Some countries like Austria added large PHES capacities even with having no nuclear power at all. As Figure 2.2 illustrates the annual percentage rate of development of PHES in European countries has slightly expanded since 2008, which is thought to have been a response to the increasing of energy requirement through the 90’s and anticipation of increased wind generation. The 430 MW Reisseck II scheme in Austria (commissioned in 2014) and the expansion of the Spanish La Muela pumped storage facility by 852 MW are some of Europe’s newest PHES developments (HydroWorld,2013).

2.2.2 Japan

Japan has historically developed PHES system to complement its nuclear generation and to provide an alternative solution to fossil fuel peaking units. Japan chose nuclear power as a primary electricity source generation. For energy security reasons, Japan has installed a large capacity of PHES systems to complement its nuclear power and provide peak electricity. Furthermore, it also does not have any electrical interconnections to other nations (unlike France, for instance, which is a significant exporter of nuclear-generated power in the United Kingdom, Germany, Italy, Switzerland and Spain). This adds to the value of flexible generating plants and explains, why the percentage of PHES capacity is significantly higher than in many other countries. The mountainous in Japan is perfect for PHES installations, although the majority of the most suitable sites have been developed (Anuta, Taylor, Jones, McEntee, & Wade, 2014).

2.2.3 China

Compared to Europe, USA and Japan, the development of PHES in China occurred relatively recently as shown in Figure 2.2. Although the initial PHES scheme (11 MW) was designed in 1968 and then the second in 1975. Expansion after this stayed dormant until the 1990s. Since then it has developed very quickly for many reasons. Electricity demand has been increasing with China's quick economic growth. PHES can be considered as significantly helpful to bridge the valley-to-peak gap in addition to maximizing grid-reliability. The regional targets for carbon reduction and the rapid development of wind energy in North in addition to West China, with poor transmission infrastructure are additionally regarded as important drivers for enhanced PHES development (Zeng, Zhang, & Liu, 2013). At the end of 2013, the overall hooked up wind capacity in China was 91 .4 GW.

China's high share of coal-based power generation is another driver for more flexible generation, as most plants are large scale (> 300 MW), less efficient and less economic to operate at partial load. The expansion in PHES capacity is occurring alongside the significant expansions of conventional hydro generation ("China | International Hydropower Association," 2015).

2.2.4 USA

As shown in Figure 2.2, the most of PHES stations in the United States were designed in the period 1960 – 1990 (Yang & Jackson, 2011). This period was aligned with significant increases in nuclear capacity. (Denholm et al., 2010), note that the significant increases in the cost of crude oil and gas in the 70's along with uncertainty about future prices, guided utilities in the USA to evaluate PHES as alternatives to fossil fuel peaking units. With lower electricity price ranges for PHES stations than conventional peaking stations more recently, PHES was often more attractive economically. Since 1990, there has been the minimal deployment of PHES in the USA as a result of Subsequent decreases in the price of oil and gas, as well as large decreases in the capital costs of Combined Cycle peaking units. A number of articles have indicated that the USA owns a PHES potential greater than 1000 GW (Yang & Jackson, 2011).

2.2.5 India

In India, the first pumped storage station was the 770 MW Nagarjunasagar plant, which was completely commissioned in 1981. Between 1981 and 1998 another 742 MW of PHES was installed, and then one more 3450 MW was installed between 2003 and 2008. The motivation to install PHES in India comes primarily from the desire to meet peak electrical demand; the peak power capacity is short of the peak demand in most states by 10-15%. Therefore, the aim for pumped hydro plants is to shift electricity from off-peak to peak hours (Sivakumar, Das, Padhy, Senthil Kumar, & Bisoyi, 2013).

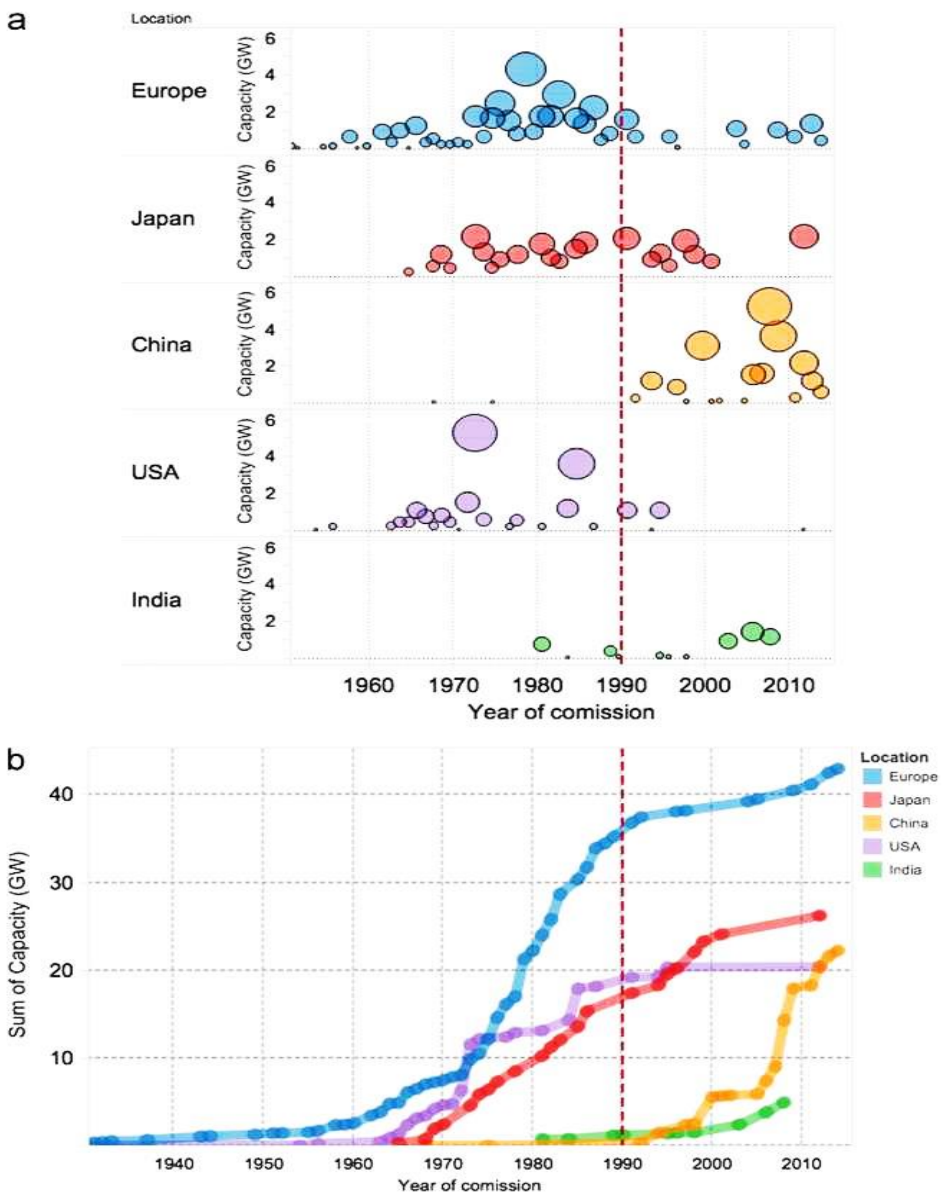

Figure 2.2: (a) Historical PHES deployment in Europe, Japan, China, USA and India (GW). The dots represent each year in which at least one PHES plant was commissioned, and have an area proportional to the capacity commissioned in that calendar year. (b) Cumulative sum of PHES deployment power capacity (GW). The list of PHES plants included is available to download ("Energy Storage Sense," 2012.)

2.3 Advantages of PHES for Wind Integration

The benefits associated with inserting wind power to the electrical power system is summarized as the following: 1. Reduction of total generation cost since much less fuel is used in conventional stations and 2. Reduction in carbon emission while less fossil fuel is burned. However, as a result of the natural variability of wind, expanded wind power integration can create harmful effects on the power system reliability. These types of negative impacts can potentially require an increase in the cost of maintaining the same level of power system reliability, often called wind integration cost. Furthermore, these negative impacts can potentially offset the advantages of wind power and grow to be significant, while additional wind power is installed into the power system (Holttinen, 2008). It is very important to determine these types of negative impacts to make sure that they mitigate just a smaller part of the advantages. There are many scientific studies completed on integrating PHES with wind farms as a technique to offset wind variability problems. Some advantages of PHES related to wind power integration as a result of these scientific studies are discussed below (Namgyel, 2012).

PHES is typically aligned with wind stations to increase economic profit. At certain times of low energy cost, the wind stations as an alternative to selling their power to the grid, it can be used to pump water from a lower water reservoir, and then keep in the upper reservoir. Whenever the energy price increases above a certain threshold level, stored water is released back into the lower reservoir generating electricity, and it is sold to the grid. Wind power is often sold to the grid within this period of high energy cost. In Alberta, in anticipation to 700 MW of wind energy in the future, a model which involved a 40 MW Castle River wind farm and a 40 MW PHES at Oldman dam was suggested. The result demonstrates that when wind power generating individually was profitable, the productivity of wind power generation expanded by a factor of four when it was connected with PHES (Nickel, 2006).

PHES is commonly used in remote areas to benefit from wind power rejection. Involvement of PHES into the power system of an isolated location, helps effectively to mitigate a rejection power that is generated by wind farms (J. S. Anagnostopoulos & Papantonis, 2008).

Utilization of PHES to handle wind power variability is a developing trend globally. There are many scientific studies on using PHES for integrating wind energy. All of these studies referred to show considerable benefits of combining PHES in the power system. Some of these studies will be reviewed here.

(Bakos, 2002) examined the operation of a combination wind/hydro power in a selected application on the island of Ikaria in Greece system intending at generating low-cost electricity. A Monte Carlo simulation code was created to simulate the operation of the entire installation, to enable a suitable selection of component standards and location meteorological data to be applied to increase prediction capabilities. The code repeatedly integrates to determine the immediate amount of the water reservoir, and also the present condition of wind-farm energy production. According to these two variables, a logical decision tree is designed to determine whether the wind, accumulated wind and hydro energy can satisfy the needs of the local grid in the island of Ikaria.

Some studies concentrate on the development of an optimal method for PHES integration. (Castronuovo & Lopes, 2004), conducted an optimization technique to assist recognizing the perfect hourly and daily strategy for the operation of a merged wind–hydro pumping storage power station. Based on the solution of the optimization problem, it is easy to figure out the hourly operation of the water pump station (WPS), small hydro generator and also wind generator, such that it can raise the power plant operation revenue.

(Kusakana, 2016), designed a model to obtain the optimal daily operation planning to be executed in a hybrid system consists of a photovoltaic unit, a wind farm, a PHES system in addition to a diesel generator. This model seeks to reduce the use of the diesel generator while maximizing the utilization of the solar photovoltaic unit, wind units and PHES system. The simulation results indicate that using the pumped hydro storage ability; it is possible to handle any load operational limitations which often need a quick response from the power generation or storage system.

Some research studies conducted a numerical research of the most efficient sizing and design of a pumping plant unit in a hybrid wind-hydro station. (John S. Anagnostopoulos & Papantonis, 2007) introduced a numerical research in the wind-hydro station. The standard model which contains some identical pumps working in parallel is analyzed compared with two different other configurations, making use of one variable-speed pump or just a special group of smaller sized jockey pumps. The target is to decrease the quantity of the wind energy that cannot be converted to hydraulic energy in the storage tank resulting from power operating limitations of the water pumps in addition to the which will lead to step-wise operating of the pumping plant. The plant performance for a certain time of one year is simulated by an extensive evaluation algorithm, which additionally conducts an extensive economic analysis of the plant employing dynamic evaluation methods. A preliminary examine of the whole plant sizing is completed at first applying an optimization tool dependent on evolutionary algorithms. The operation of the three analyzed pumping station units is then estimated and then discussed in a comparative study. The outcomes show that the making use of a variable-speed pump constitutes the most effective and profitable solution and its superiority is more pronounced for less dispersed wind power potential.

(Benitez, Benitez, & van Kooten, 2008), designed a nonlinear mathematical optimization program for checking out the economic and environmental effects of wind penetration in electrical grids and estimating how hydropower storage can be used to offset wind power intermittency. Also, (Foley, Leahy, Li, McKeogh, & Morrison, 2015), have designed a technical, economic and environmental long-term creation extension planning analysis of a test system with high wind power generation. This research is unique in that, it captures reserve needs in addition to generation prices and carbon emissions using an optimized power dispatch and unit commitment model.

In the current study, the difference from previous studies is that PLEXOS Software will be used to evaluate the practical approach to building the storage system along with high integration level of wind. The present study will consider Jordan-Tafila wind farm as a reference station for the future expansion in wind integration level in Jordan. Other sites will be explored for the opportunity of being candidate sites to be utilized as hydropower storage such as the large dams in Jordan. Upon to the author knowledge, this will be the first research that is concerned with using hydropower storage system to regulate the power supply from the wind farms in Jordan to the national grid.

Chapter Three

Location survey

3.1 Introduction

In future energy systems in Jordan with high shares of non-dispatchable renewable electricity generation, storage system will play a key role. Furthermore, the rapid increase in the expansion of renewable energy systems will lead to an urgent need to regulate the electricity flow into power networks. So, the main goal of this research is to explore the opportunity in Jordan to design a PHES system to avoid the loss of energy generated by the wind farms at off-peak demand by using the excess energy to pump water to high elevation reservoir. At peak demand, this high potential energy water will be released back to operate hydropower turbines that generate electricity according to the demand on the grid.

Jordan has many huge dams in the southern and northern parts of Jordan that are surrounded by mountains and hills with good heights. Six dams were built in the north and the middle of Jordan valley as it may be seen in Figure 3.1 with an overall storage capacity of 178.7 MCM. These dams are: King Talal, Ziglab,Wadi Al- Arab, Karameh, Shuaib and Kafrein . Three additional dams, Tannur, Mujib and Walah are in the southern part with an overall storage capacity of 57.7 MCM. AL-Wehda dam which is located on the border between Jordan and Syria has 110 MCM storage capacity. Stored water from these dams is being used for livestock, ground water recharge, irrigation and also to generate electricity by hydro generators. All the data that is needed is collected from JVA and a sample of the data can be found in appendix A ("Jordan Valley Authority - Web Presence," 2017).

Figure 3.1: Dams in jordan (Current and Planned Infrastructural Projects - Fanack Water)

3.2 The geographical requirements of the candidate sites

In general, PHES system consists of two reservoirs with high elevation difference. The candidate locations for installation of PHES system should be situated on high elevation areas such as hill or mountain and also it should be near to the water sources. The upper reservoir is on top of a mountain, whereas the lower reservoir is at the bottom of the mountain. The powerhouse with the generators is definitely in between the two reservoirs but very close to the lower reservoir. One of the aims of this research is to search for suitable natural basins nearby an existing water reservoirs (dams). To decrease the construction cost of PHES system, the location should have the following properties:

1. The nature of the site should be able to keep water.
2. The elevation between the upper and lower reservoirs should be high enough to allow construction of PHES. For a certain power station, the reservoir storage requirement and the capacity of the water conduit are inversely proportional to

head. Therefore, the cost of the reservoir and water conduit is greatly reduced when the site has a high head.

3. The distance of water conduit has to be as short as possible. This is mainly necessary for the locations with the lower head. The economic length for a water conduit is function of head and can be identified in terms of the whole length to head (L/H) ratio. The maximum acceptable L/H ratio range is from 10 to 12 for high-head sites (360 m and above) and about 4 to 5 for low-head sites (150-180 m) (Namgyel, 2012).
4. Reservoir candidate locations should have least excavation work to reduce the capital cost of construction.
5. The candidate sites should be located near the grid to reduce power transmissions cost.

3.3 Energy storage capacity

To determine the amount of energy that can be stored by the PHES system in a dam. The volume of water that is needed to estimate the electrical energy that can be converted into potential energy in the high elevation storage can be calculated according to the following steps:

1- Identify the rated pumping head.

2- Calculate the volume flow rate of water when pump operates with 1 MW rated power to elevate water to rated head into upper reservoir by using equation (3.1)

$$Q_P = \frac{P_P \times \eta_P}{g \times \rho \times h} \tag{3.1}$$

Where:

Q_P: Rated volume flow rate (m^3/s).

P_P: Rated Pump Power (W).

η_P: Pump efficiency.

g: Acceleration of gravity $(9.8\,m/s^2)$.

ρ: Density of water $(1000\,Kg/m^3)$.

h: Head (m).

3- Identify pump continuous operation time in hours at a rated power in a certain interval.

4- After calculating the value of rated flow rate in step 2 and identifying the number of hours in step 3, the required volume of the upper reservoir can be estimated by using equation 3.2.

$$V_R = Q_P \times T \qquad (3.2)$$

Where:

V_R: Volume of the upper reservoir.

T: Rated pumping time in second.

Now it is possible to expand the system capacity by multiplying the required rated pumping power by the volume of the upper storage that was used to store energy for only 1MW rated pumping power.

3.4 Candidate sites in Jordan

It is important to mention that the geographical requirements of the candidate sites are not easy to be met. However, it is necessary to explore and find the best locations that can achieve the maximum possible of the requirements of PHES installation to reduce the capital infrastructure cost of the whole project. Jordan, as previously indicated has a good potential sites to utilize this kind of storage system as result of the natural terrain's specifications nearby the dams.

3.4.1 King Talal Dam

As shown in Figure 3.2, King Talal Dam is a huge dam in the mountains of northern Jordan, across the Zarqa valley. As shown in table 3.1 the dam was initiated in 1971, with the primary construction getting completed in 1978 at an elevation of 92 .5 meters. In 1984, to match the country's increasing water demands, the dam was expanded to a height of 106 meters, a project which was completed in 1988. The main purposes of the dam are to store winter rain water, to treat sewage water that is drawn from Amman and Zarqa to be treated in As Samra station, to irrigate Jordan Valley farms and to generate electricity. There are two small hydro power units (Francis turbine) installed in the King Talal Dam with rated capacity of 5 MW.

Figure 3.2: King Talal dam

Table 3.1: King Talal dam information (Jordan Valley Authority, 2015)

Location	Zarqa valley
Type	Earth - fill
Purpose	Irrigation
Height	108 m
Storage capacity	74 MCM
Construction	Completed in 1977, raised in 1987

King Talal Dam has an excellent potential to construct PHES system as shown in Figure 3.3. Two candidate locations are identified which have proper height difference that ranges from 200 to 220 m and have enough suitable area where the upper reservoir can be constructed.

Figure 3.3: Candidate locations in King Talal dam

The candidate locations in the dam area are close to the electric grid. This is advantageous regarding the construction cost, (i.e. Reducing the electrical transmission expenses). Figure 3.4 indicates that the distance between the upper and bottom storage is approximately 1.25 km which is acceptable from design point of view. The elevation of upper storage is 384 m above the sea level, whereas the powerhouse location hieght is 179 m near the end of the hill.

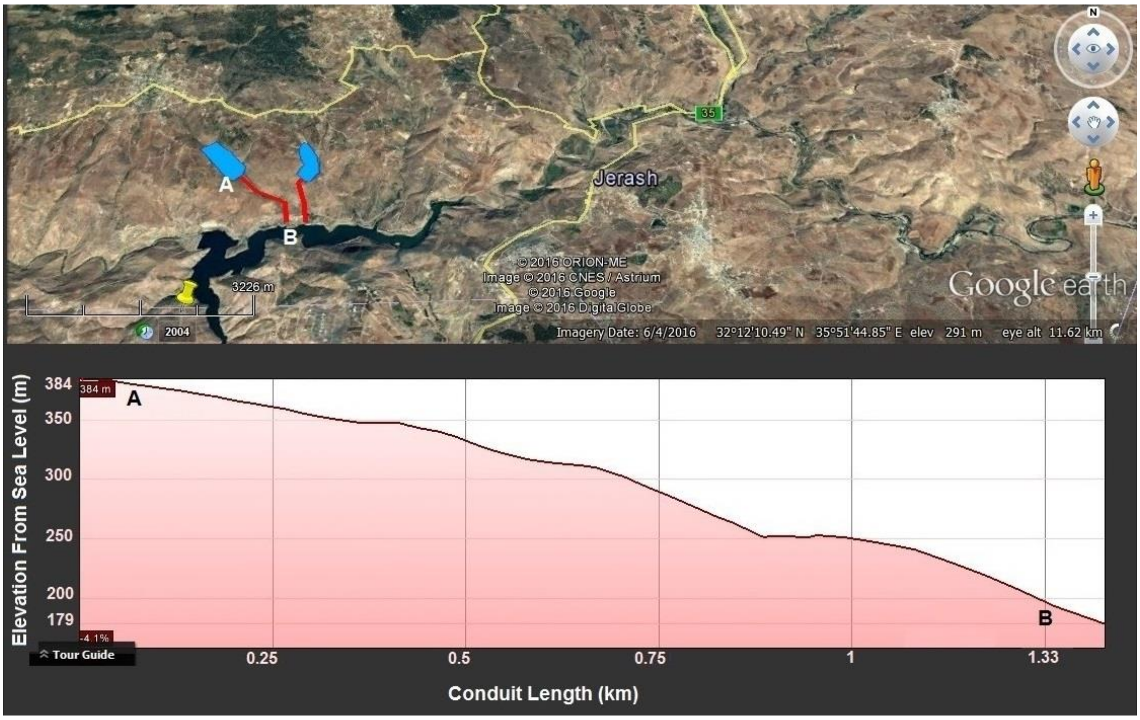

Figure 3.4: The curve in the bottom graph shows the Elevation difference profile between the points A and B marked in the picture of King Talal dam

To estimate the amount of electrical energy that can be stored in the proposed PHES system at King Talal dam, an intensive analysis of the water balance for the dam including the storage volume, inflow and outflow rate volume for at least 3 years should be performed to guarantee that the water level is available all through a year that will make the PHES work properly. As mentioned before the capacity storage of King Talal dam is 74 MCM. Figure 3.5 shows the water balance through the period from 2011 to 2017. The minimum value of storage volume through this period was about 20 MCM on January first of 2011/2012/2013.

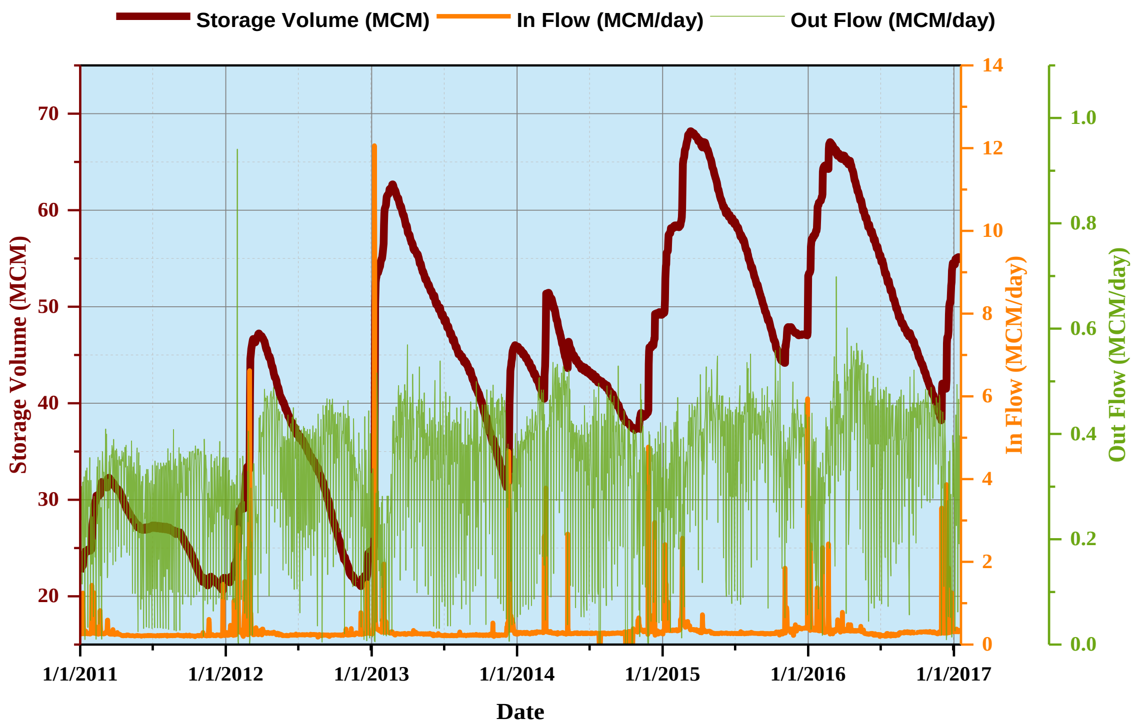

Figure 3.5: Water balance of King Talal dam

By applying the procedure in section 3.3, the volume of water that is needed to operate PHES system in the candidate locations in king Talal dam can be calculated. For the rated pumping head at the proposed site of height difference 205 m and by using equation 3.1 , the rated discharge from the pump at rated head is calculated to be 0.45 m^3/s . Assume the pump will be continuously operated for 12 hours, by using equation 3.2, the required volume of upper storage is 19.3×10^3 m^3.

Now it is easy to expand the system capacity by multiplying the required rated pump power by the volume of the upper storage that was used to store water for only 1 MW rated pumping power for 12 hours. Assume there is a wind farm with 250 MW capacity then the volume of the upper reservoir that needed to store energy for 12 hours is 4.8 MCM. Which is only 24% of minimum stored volume that King Talal dam reached on first January of 2011/2012/2013. As shown in Table 3.2 the area of the first location is $190.6\times10^3 m^2$ and it is a natural basin. Additional miner work at the site is required to get the depth of 25 m which is needed for the designed volume of 4.8 MCM that can store energy of 3000 MWh in daily recycle, and for the second location only 15 m depth will be needed to obtain the designed volume because it is a natural basin and has a larger area of $310.4\times10^{3}\ m^{2}$.

Table 3.2: The specification of the candidate sites in king Talal dam

The candidate places	**Latitude & longitude**	**Projected Area (m^2)**	**Depth (m)**	**Height difference (m)**
Location 1	32°12'10.91"N 35°48'11.53"E	190667	Dependent on the capacity	384-179=205
Location 2	32°12'14.22"N 35°49'3.37"E	310384	Dependent on the capacity	384-179=205

Figure 3.6 indicates the relation between the expected daily energy that can be stored in king Talal dam and the volume of upper reservoir which is needed to store this amount of electrical energy. It also shows the percentage of upper reservoir volume to the minimum storage volume level in the existing lower reservoir (dam).

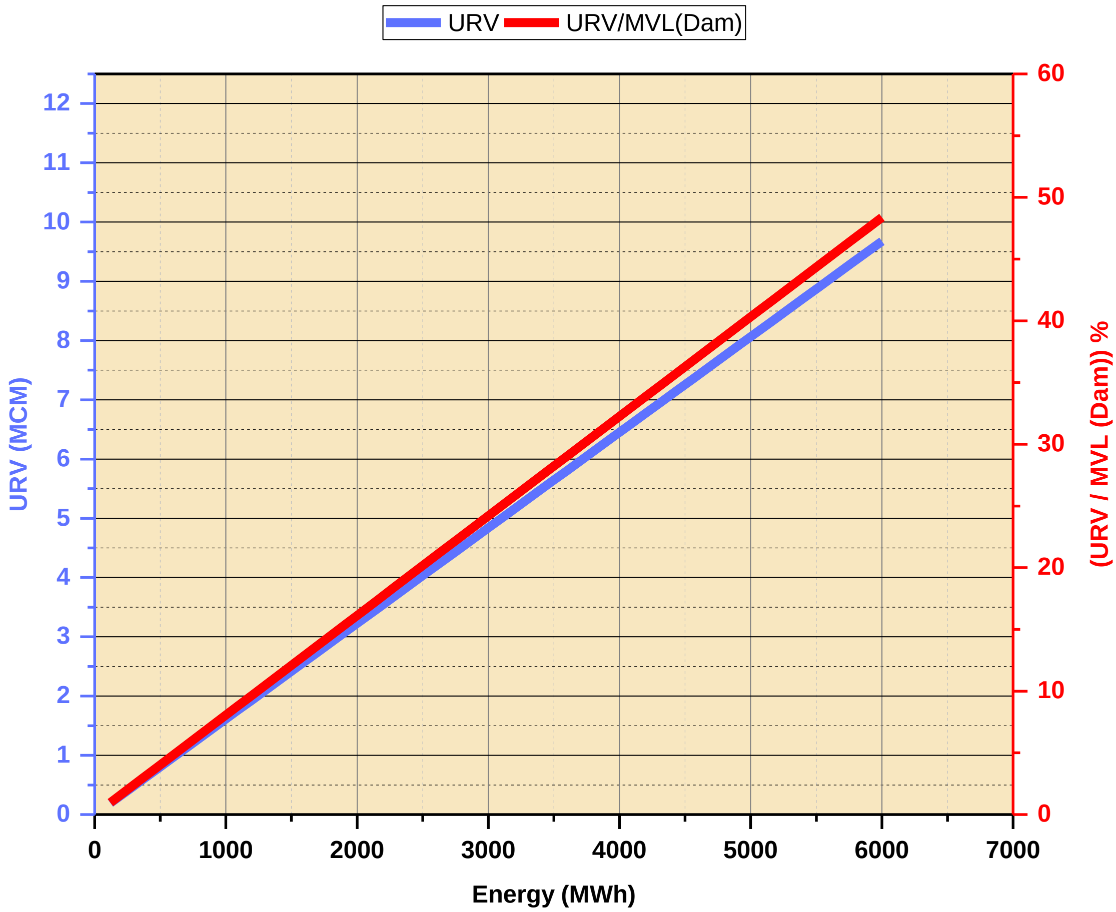

Figure 3.6: Expected daily energy in King Talal dam with respect to the Upper Reservoir Volume (URV) and the ratio of URV with the Minimum Volume Level (MVL) of existing lower reservoir (dam)

3.4.2 Al-Wehdah Dam

As shown in Figure 3.7, AL-Wehdah dam is an 110-m height roller-compacted concrete gravity dam on the Yarmouk River at the border between Syria and Jordan. It is able to hold up to 115 MCM of water which is constructed to supply Jordan with water for both human consumption and agriculture. Table 3.3 shows the specifications of this dam.

Figure 3.7: Al-Wehdah dam

Table 3.3: Al-Wehdah dam information (Jordan Valley Authority, 2015)

Location	North of Jordan, at Yarmouk River, at AL-Maqaren ,120 km north of Amman
Construction	2004-2006
Type	Roller Compacted Concrete (RCC)
Height	110 m
Storage capacity	115 MCM
Purpose	Irrigation, human consumption

Al-Wehdah dam is also considered to be a Suitable site to install PHES systems as shown in Figure 3.8. Three locations are identified which have proper height difference that ranges from 265 to 275 m and have enough suitable area for each place where the upper reservoir can be constructed.

Figure 3.8: Candidate locations in Al-Wehdah dam

The candidate locations in the dam area are next to the electric grid. This should be an advantage to minimize construction cost by reducing the electrical transmission expenses. Furthermore, as shown in Figure 3.9 the distance between the upper and lower storage is varying from 570 m to 612 m which is acceptable from design point of view. The elevation of upper storage is 349 m above the sea level, whereas the powerhouse location height is 84 m near the end of the hill.

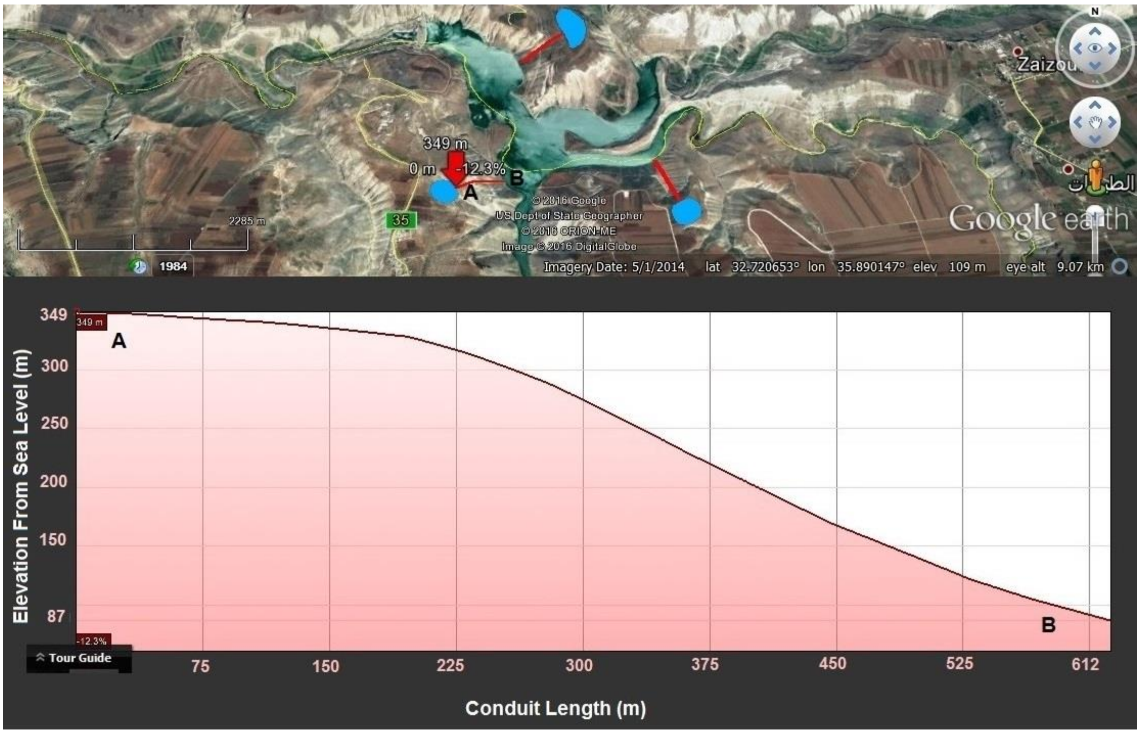

Figure 3.9: The curve in the bottom graph shows the Elevation difference profile between the points A and B marked in the picture of Al-Wehdah dam.

To estimate the amount of electrical energy that can be converted to gravitic potential energy then stored in the proposed upper reservoir at Al-Wehdah dam, a deep analysis of the water balance for the dam, including the storage volume, inflow and outflow rate for at least 3 years should be performed to guarantee that the water level is available all through a year that will make the PHES work properly. As mentioned before the capacity storage of Al-Wehdah dam is 115 MCM. Figure 3.10 Shows the water balance through the period from 2011 to 2017. The minimum value of storage volume through this period was about 5 MCM in 28/10/2011, 5 MCM in 23/8/2012, 15 MCM in 13/9/2013 and 25 MCM in 25/10/2015. The average daily outflow rate is 0.12 MCM. The PHES capacity should be less than 5 MCM which is a minimum record of dam's storage.

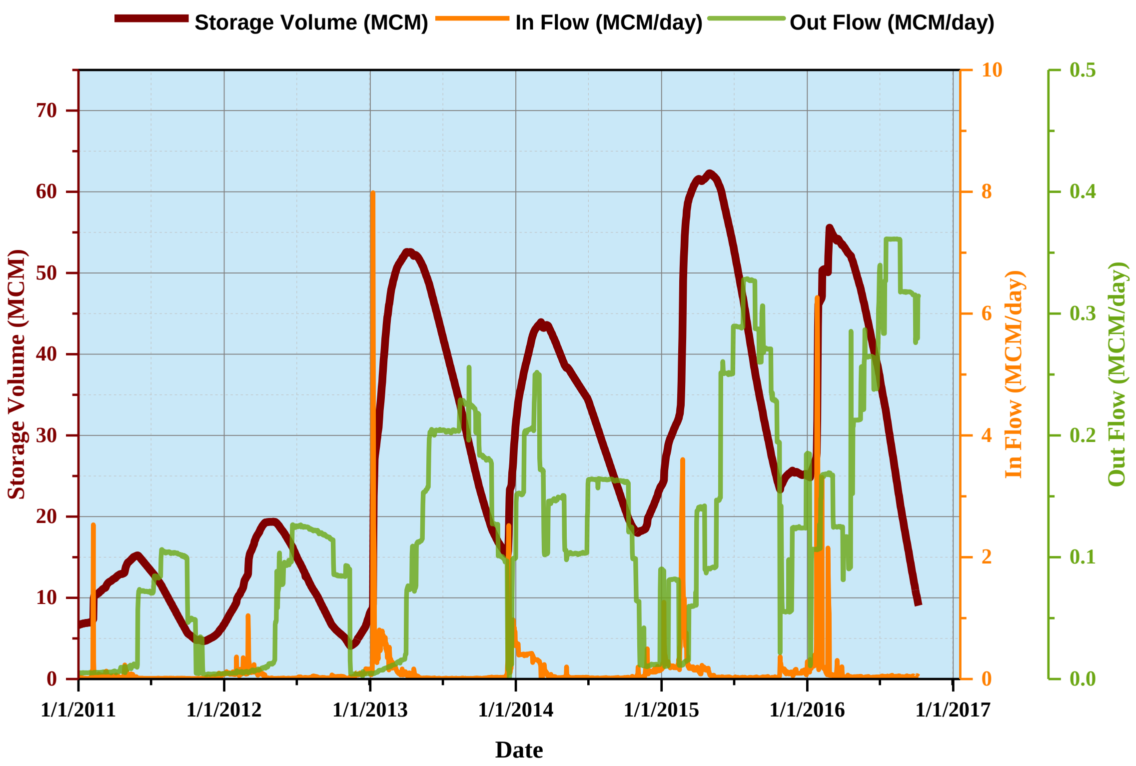

Figure 3.10: Water balance for Al-Wehdah dam

Following the prodecure in section 3.3. The rated pumping head at proposed site is 265 m, then by using equation 3.1 the rated discharge from the pump at rated head is calculated to be 0.35 m^3/s . Assume the pump will be continuously operated for 12 hours, by using equation 3.2, the required volume of upper storage is 14.9×10^3 m^3.

Using the same procedure for expanding the system capacity, by multiplying the required rated pump power by the volume of upper storage that was used to store water for only 1 MW rated pumping power for 12 hours. Assuming the required capacity equals to 100 MW then the volume of the upper reservoir that is needed is calculated to be 1.5 MCM. This is only 29.9% of a minimum stored volume that Al-Wehdah dam has reached in 28/10/2011, and 23/8/2012. As shown in Table 3.4 the area of the first location is 70×10^3 m^2 , some miner work at the site is required to get the depth of 21 m that is needed for designed volume of 1.5 MCM which can store energy of 1200 MWh in daily recycle, whereas the second location only 11.8 m depth will be needed to obtain the designed volume because it has larger area of $126.2\times10^3\ m^2$. The area of the third site is found to be $60\times10^3\ m^2$ and the upper storage depth should be 25 m to match the required volume.

Table 3.4: The specification of the candidate sites in Al-Wehdah dam

The candidate places	**Latitude & longitude**	**Projected Area (m^2)**	**Depth (m)**	**Height difference(m)**
Location 1	32°42'41.95"N 35°54'8.25"E	70000	Dependent on the capacity	350-84=266
Location 2	32°43'58.05"N 35°53'24.83"E	126185	Dependent on the capacity	350-84=266
Location 3	32°42'46.90"N 35°52'33.43"E	60000	Dependent on the capacity	350-84=266

Figure 3.11 indicates the relation between the expected daily energy that can be stored in Al-Wehdah dam and the volume of upper reservoir which is needed to store this amount of electrical energy. It also shows the percentage of upper reservoir volume to the minimum storage volume level in the existing lower reservoir (dam).

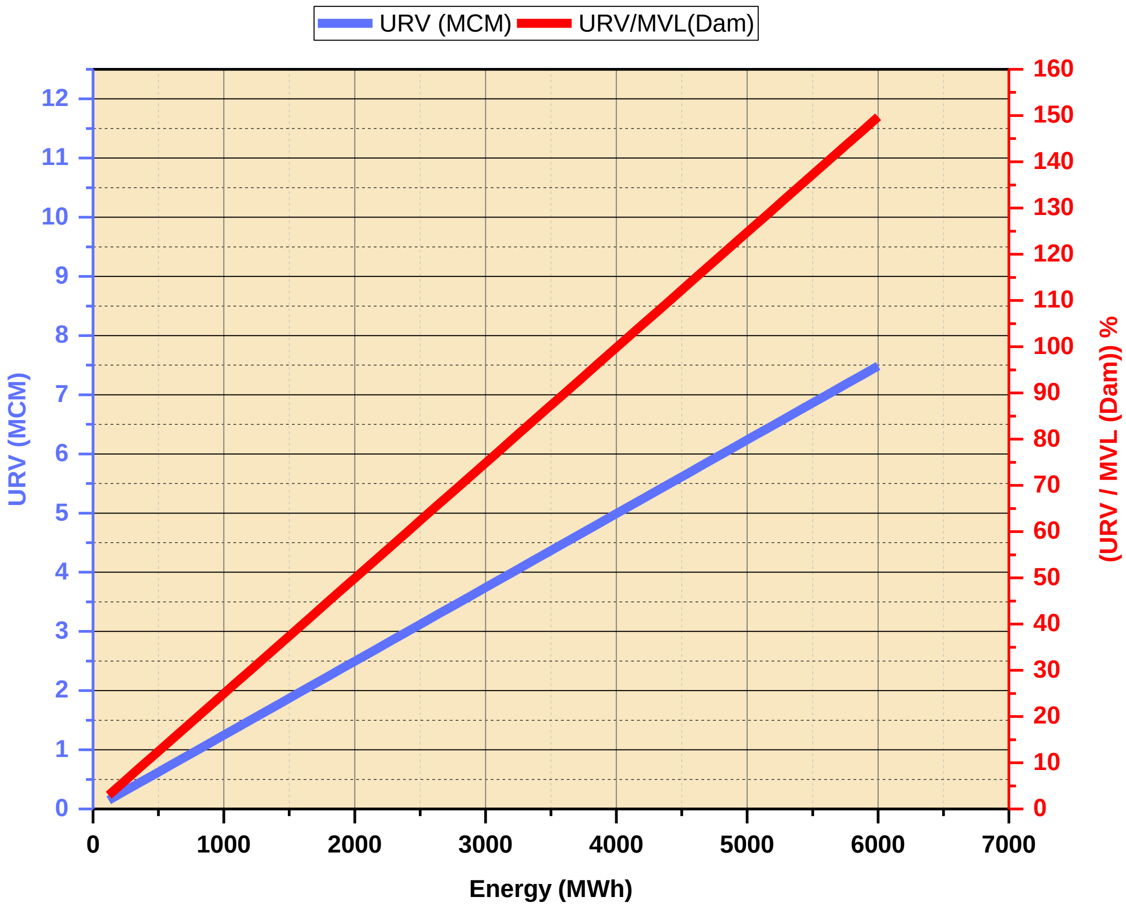

Figure 3.11: Expected daily energy in Al-Wehdah dam with respect to the Upper Reservoir Volume (URV) and the ratio of URV with the Minimum Volume Level (MVL) of existing lower reservoir (dam)

3.4.3 Wadi Al-Arab dam

As shown in Figure 3.12 Wadi Al-Arab dam is located in the northern part of Jordan valley, about 10 km south of the Tiberias lake and 25 km from Irbid City. The water arrives partially from the King Abdallah Canal that draws water from Jordan river and partly from precipitation. The water is utilized to irrigate about $12.5\times10^{6}\ m^{2}$ of land starting from Al Shuna to Al Baqura. Table 3.5 shows its specification.

Figure 3.12: Wadi Al-Arab dam

Table 3.5: Wadi Al-Arab dam specification (Jordan Valley Authority, 2015)

Location	At Wadi, Arab
Construction	Construction Completed in 1986
Type	Earth-fill
Height	83.5 m
Storage capacity	16.8 MCM
Purpose	Irrigation, Municipal, Hydropower

Wadi Al-Arab dam is situated in terrain which has excellent potential to construct PHES system. One candidate location as shown in Figure 3.13, with a proper elevation which is about 270 m**,** and has enough suitable area where the upper reservoir can be constructed.

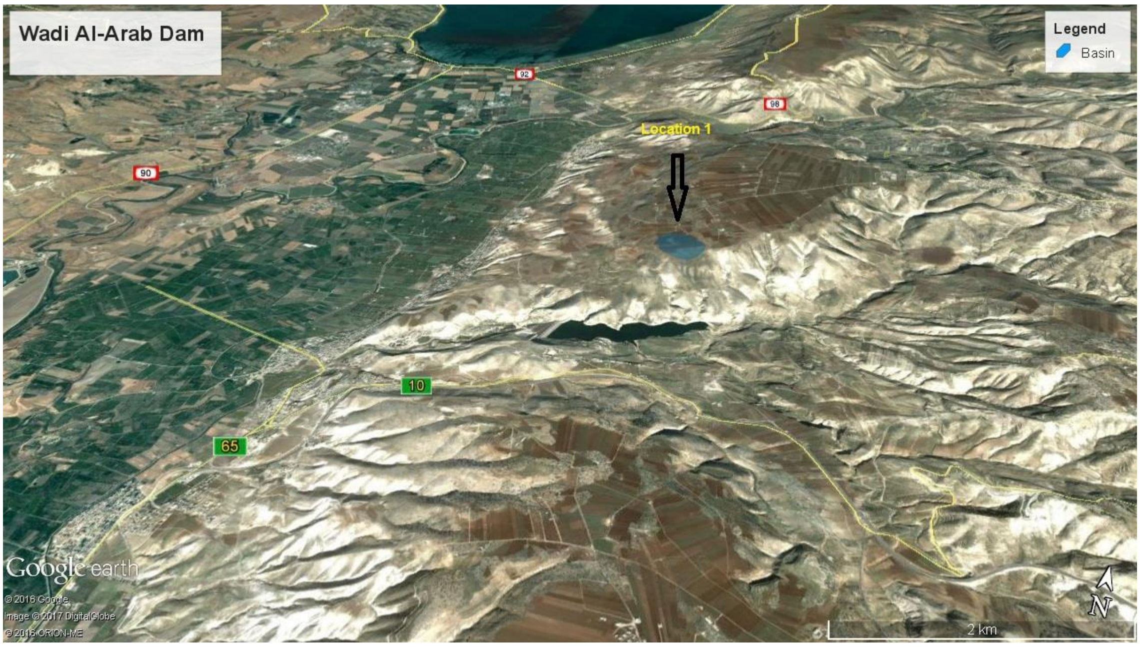

Figure 3.13: Candidate location in Wadi Al-Arab dam

The candidate location in the dam area is close to the electric grid. This should be an advantage to minimise construction cost by reducing the electrical transmission cost. Furthermore, as shown in Figure 3.14 the distance between the upper and lower storage is found to be 900 m which is acceptable from design point of view. The elevation of upper storage is 170 m above the sea level, whereas the powerhouse location height is (n-100 m) near the lower end of the hill.

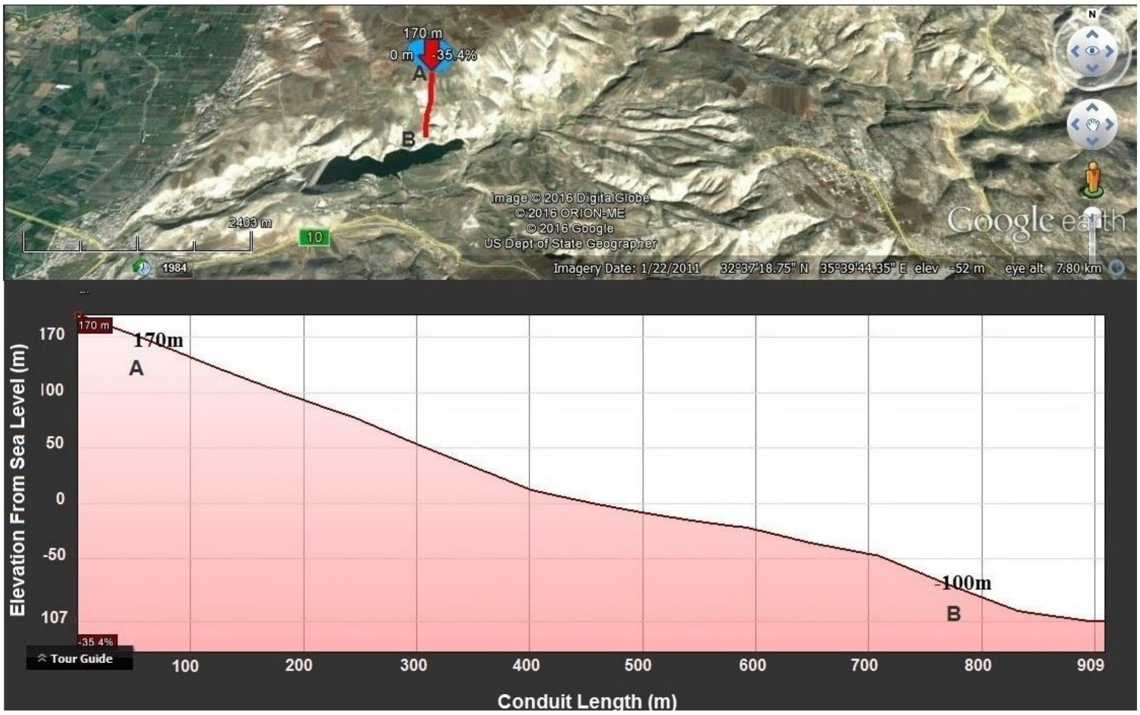

Figure 3.14: The curve in the bottom graph shows the Elevation difference profile between the points A and B marked in the picture of Wadi Al-Arab dam

The same method will be utilized to estimate the amount of electrical energy that can be stored in the proposed PHES system at Wadi Al-Arab dam. It is important to examine the water balance for the dam, including the storage volume, inflow and outflow rate for at least 3 years to find out if water level is available all through a year that will make the PHES work in a efficient way. As in Table 3.5 the capacity storage of Wadi Al-Arab dam is 16.8 MCM. Figure 3.15 shows the water balance through the period from 2011 to 2017. The minimum value of storage volume through this period was about 1.6 MCM on November ninth of 2012.

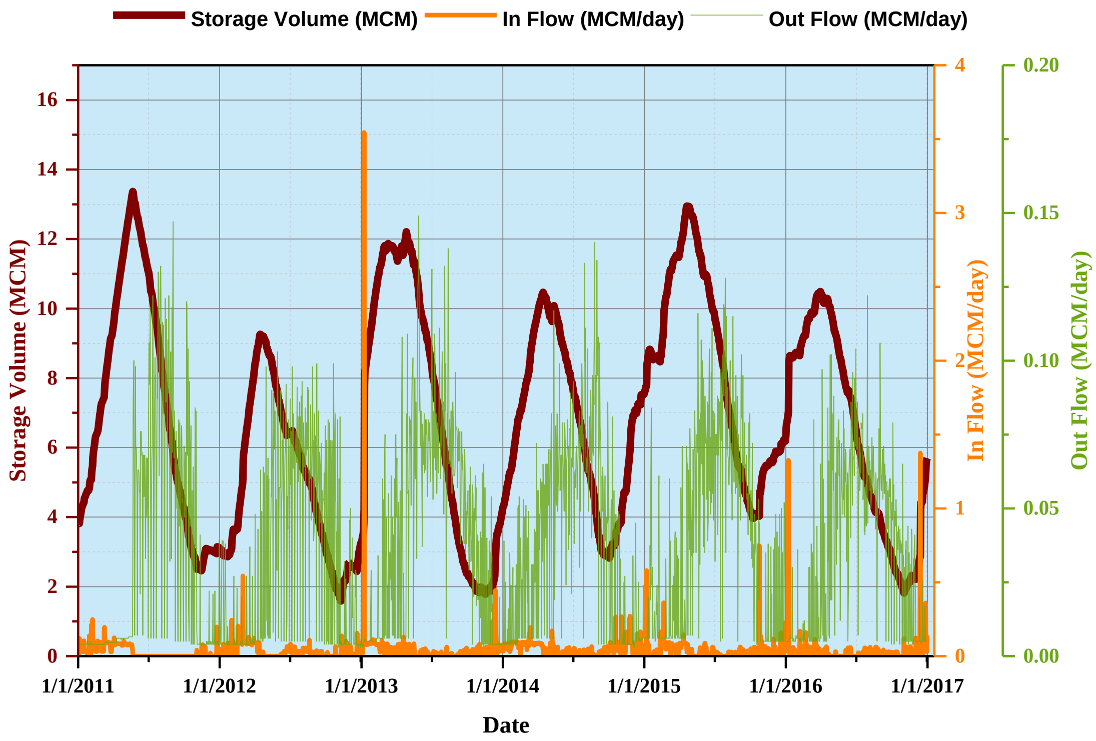

Figure 3.15: Water balance for Wadi Al-Arab dam

By applying the procedure in section 3.3, the volume of water that is needed to construct PHES system in the candidate location can be calculated. For the rated pumping head at proposed site of 270 m, using equation 3.1, the rated discharge from the pump at rated head and 1 MW pumping power is calculated to be 0.34 m^3/s . Assume the pump will be continuously operated for 12 hours, by using equation 3.2, the required volume of upper storage is $14.7 \times 10^3\ m^3$.

Now it is possible to expand the system capacity by multiply the required rated pump power by the volume of upper reservoir that is used to store water for only 1 MW rated pumping power for 12 hours. If the system capacity is 100 MW then the volume of the upper reservoir that is needed is calculated to be 1.4 MCM. Which is approximately 87% of a minimum stored volume that Wadi Al-Arab dam reached on November ninth of 2012, it is recommended to increase the dead volume limit to 3 MCM instead of 1 MCM to help PHES systems work properly. As shown in Table 3.6 the area of the first location is $247\times10^3 m^2$, some excavation at the site is required to get the depth of 6 m that is needed for designed volume of 1.4 MCM.

Table 3.6: The specification of the candidate sites in Wadi Al-Arab dam

The candidate places	Latitude & longitude	Projected Area (m^2)	Depth (m)	Height difference (m)
Location 1	32°37'55.37"N 35°38'41.62"E	247000	Dependent on the capacity	170-(-100)=270

Figure 3.16 indicates the relation between the expected daily energy that can be stored in Wadi Al-Arab dam and the volume of the upper reservoir which is needed to store this amount of electrical energy. It also shows the percentage of upper reservoir volume to the minimum storage volume level in the existing lower reservoir (dam).

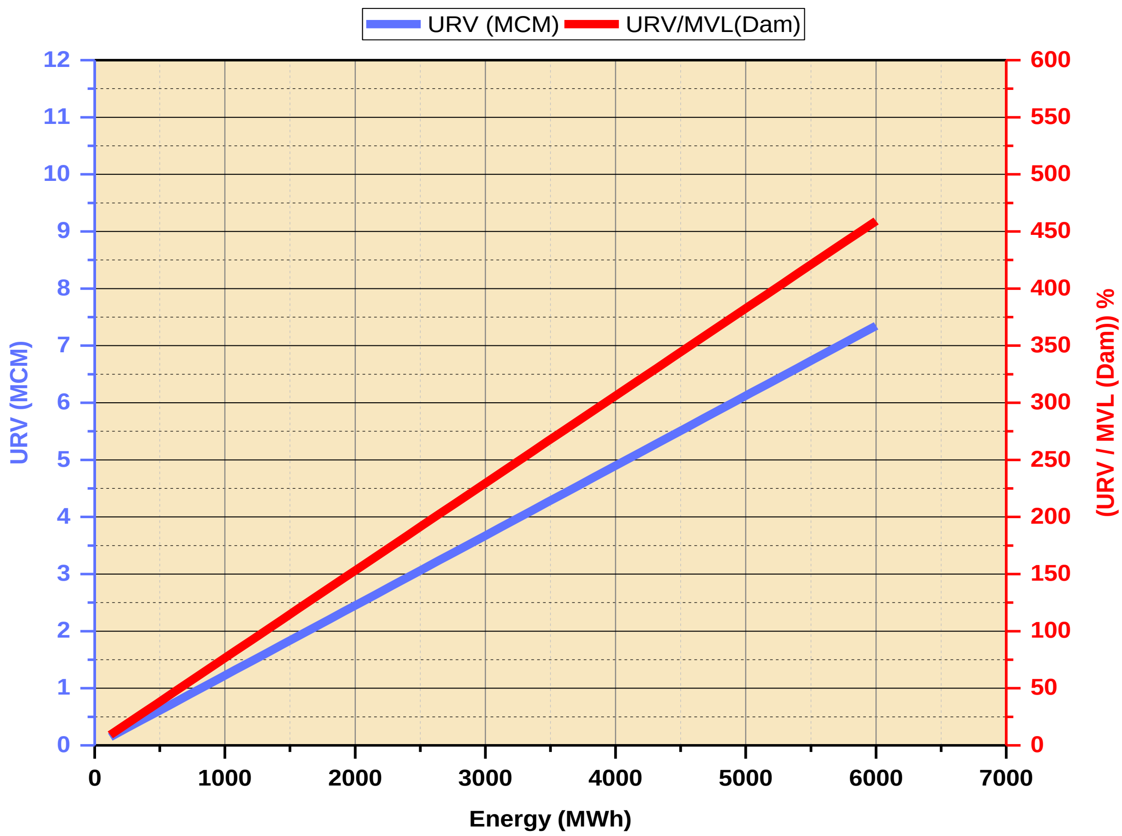

Figure 3.16: Expected daily energy in Wadi Al-Arab dam with respect to the Upper Reservoir Volume (URV) and the ratio of URV with the Minimum Volume Level (MVL) of existing lower reservoir (dam)

In summary as shown in Table 3.6 the candidate location has large area with proper elevation which means that it is a favorable site but the concern here is the small dead volume limit of the dam which is 1 MCM. So it is recommended in the future to increase the dam dead limit, to allow PHES system work in an efficient manner and also expanding the proposed storage capacity.

3.4.4 Al-Mujib Dam

As shown in Figure 3.17 Al-Mujib dam is situated in Wadi Mujib, between the governates of Madaba and Al-Karak. It is a rolled concrete (RCC) dam with abutments of clay-core rockfill. The construction work has finished in 2004, after six years of construction. Table 3.7 shows its specification.

Figure 3.17: Al-Mujib dam

Table 3.7: Al-Mujib dam specification (Jordan Valley Authority, 2015)

Location	On Wadi Mujib,100 km south of Amman
Construction	Construction Completed in 2003
Type	RCC central section with overflow stepped spillway and zoned Earth fill Wing embankments
Height	62m
Storage capacity	31.2 MCM
Purpose	Municipal & Industrial supply and irrigation

Al-Mujeb dam is considered to be a Suitable site to install PHES system as shown in Figure 3.18. One location is identified which has proper height difference of 511 m. The location has enough suitable area where the upper reservoir can be constructed. But the earth layers there are mainly basalt which may need additional cost to install the storage.

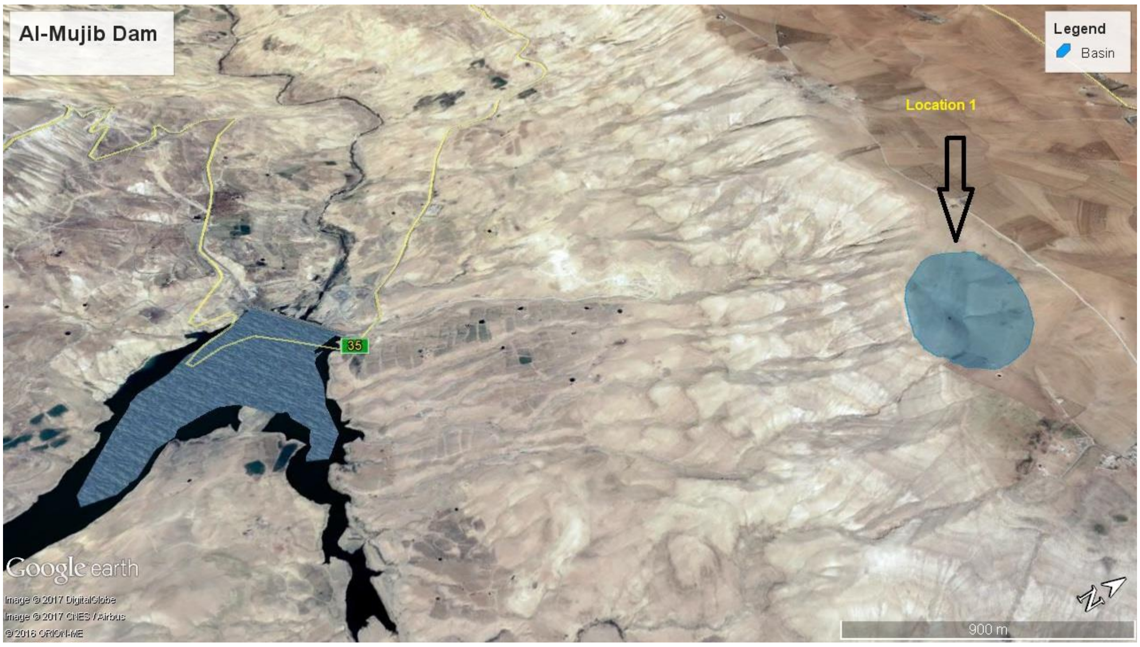

Figure 3.18: Candidate location in Al-Mujib dam

The candidate location in the dam area is close to the electric grid. This should be an advantage to minimise construction cost by reducing the electrical transmission cost. Furthermore, as shown in Figure 3.19 the distance between the upper and lower storages is approximately 2.55 km which is acceptable from design point of view. The elevation of upper storage is found to be 707 m above the sea level, whereas the powerhouse location height is 196 m near the end of the mountain.

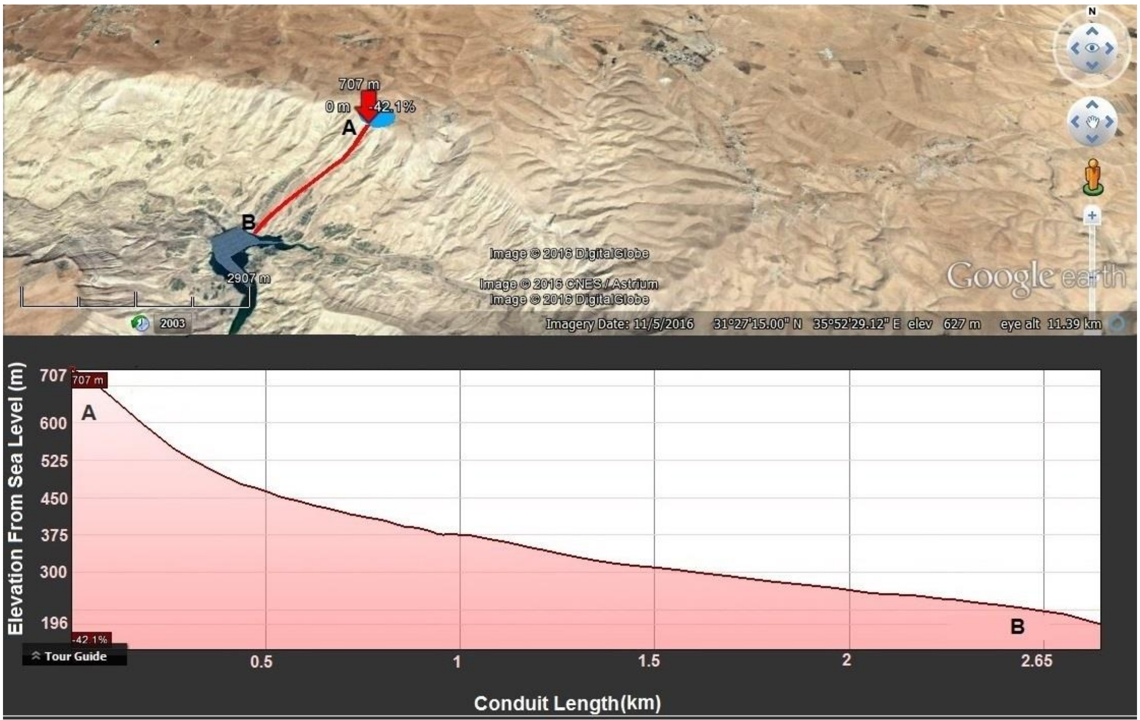

Figure 3.19: The curve in the bottom graph shows the Elevation difference profile between the points A and B marked in the picture of Al-Mujib dam

To estimate the amount of electrical energy that can be stored in the proposed PHES system at Al-Mujeb dam an intensive analysis of the water balnce for the dam, including the storage volume, inflow and outflow rate for at least 3 years should be performed to find out if water level is available all through a year that will make the PHES work in a sufficient way. As in Table 3.7 the capacity storage of Al-Mujeb dam is 31.2 MCM. Figure 3.20 Shows the water balance through the period from 2011 to 2017. The minimum value of storage volume through this period was about 5 MCM in 8/1/2013.

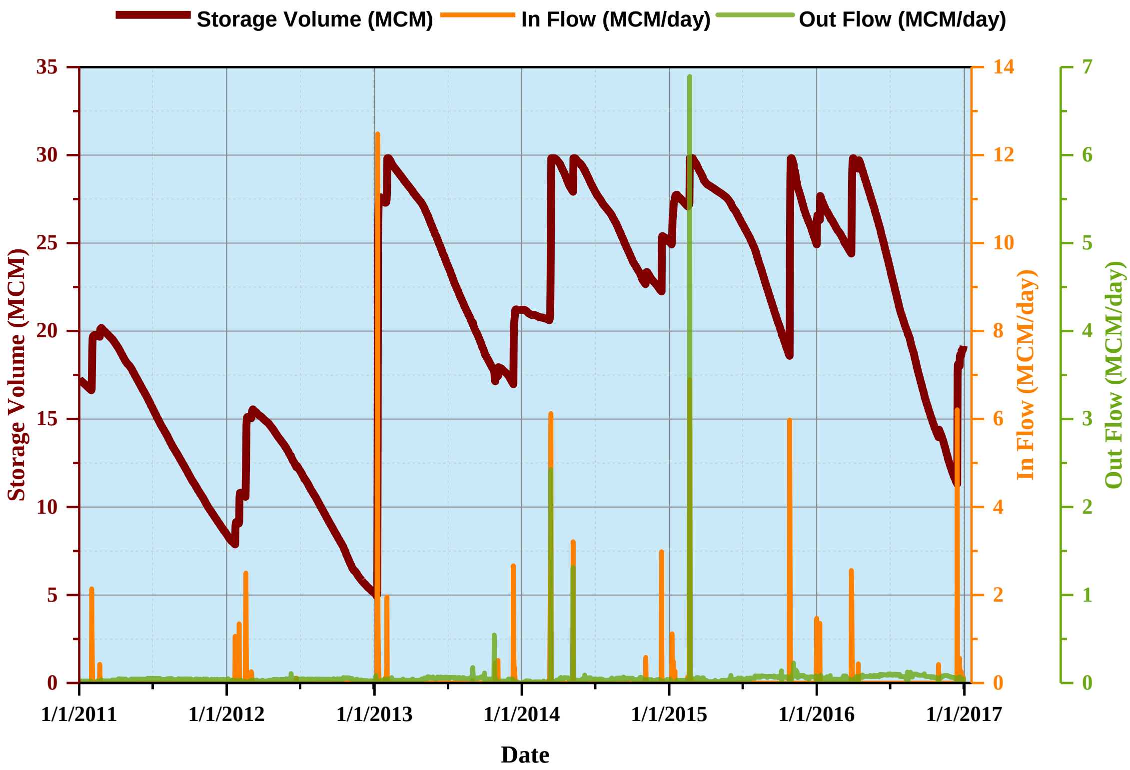

Figure 3.20: Water balance for Al-Mujib dam

According to the procedure presented in section 3.3, the volume of water that is needed to construct PHES system in the candidate location can be calculated. For the rated pumping head at proposed site of 511 m and by using equation 3.1, the rated discharge from the pump at rated head and 1 MW pumping power is calculated to be 0.18 m^3/s . Assume the pump will be continuously operated for 12 hours, by using equation 3.2, the required volume of upper storage is 7.7×10^3 m^3.

Now it is easy to expand the system capacity by multiplying the required rated pump power by the volume of upper storage that was used to store energy for only 1 MW rated pumping power for 12 hours. Assume there is a wind farm with 200 MW capacity then the volume of the upper reservoir that is needed is 1.5 MCM. Which is 30% of a minimum stored volume that Al-Mujeb dam reached in 8/1/2013. As shown in Table 3.8 the area of the first location is 285.6×10^3 m^2 , some miner work at the site is required to get the depth of 5 m that is needed for designed volume of 1.5 MCM which can store energy of 2.4 GWh daily.

Table 3.8: The specification of the candidate sites in Al-Mujib dam

The candidate places	**Latitude & longitude**	**Projected Area (m^2)**	**Depth (m)**	**Height difference(m)**
Location 1	31°27'53.86"N 35°50'24.29"E	285600	Dependent on the capacity	707-196=511

Figure 3.21 indicates the relation between the expected daily energy that can be stored in Al-Mujib dam and the volume of upper reservoir which is needed to store this amount of electrical energy. It also shows the percentage of upper reservoir volume to the minimum storage volume level in the existing lower reservoir (dam).

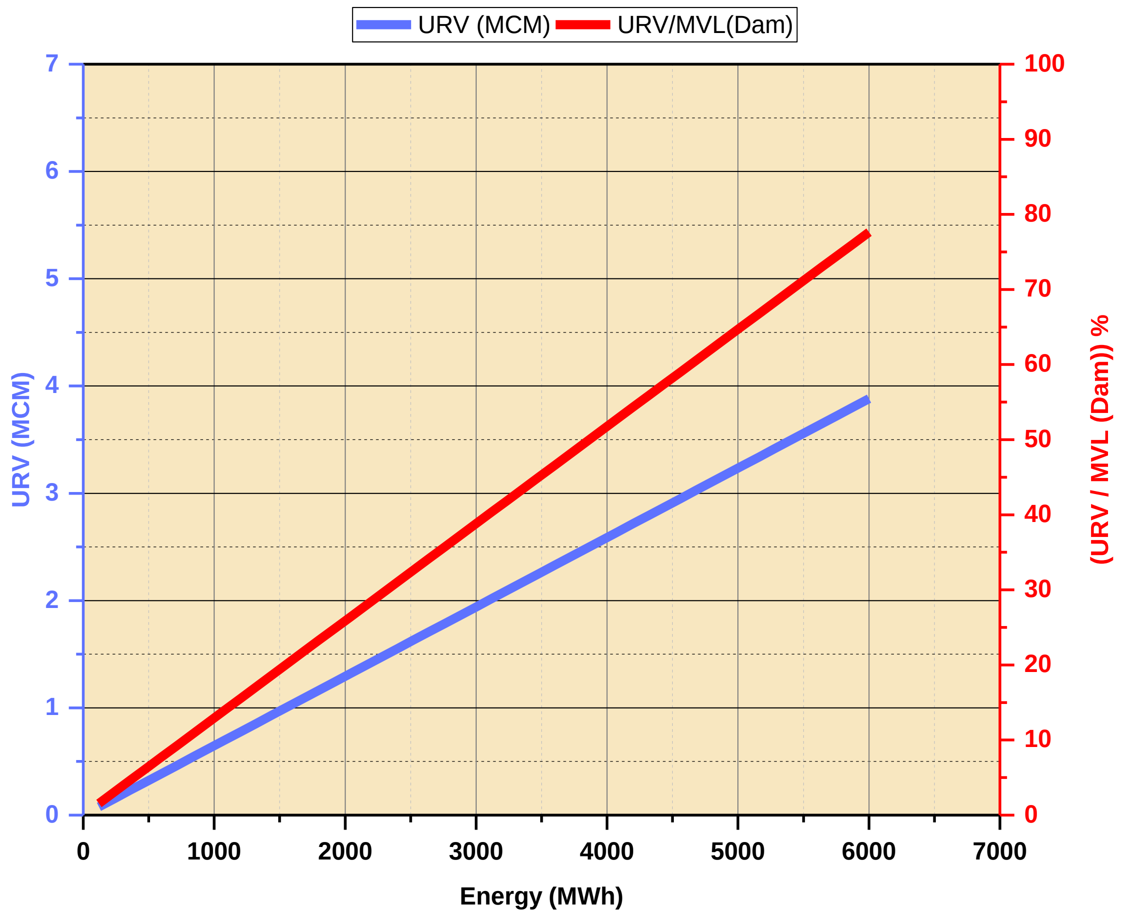

Figure 3.21: Expected daily energy in Al-Mujib dam with respect to the Upper Reservoir Volume (URV) and the ratio of URV with the Minimum Volume Level (MVL) of existing lower reservoir (dam)

In summary, Al-Mujeb dam is the best site to construct this storage system in Jordan, it has a high elevation up to 511 m and acceptable distance between the upper and lower storages.

3.4.5 Al-Walah Dam

As shown in Figure 3.22 Al-Walah dam is located at about 60 km south of Amman city at wadi Al-Wala. The dam construction was started in 1999 and finished in 2002. Also, the impoundment was initiated in 30/10/2002. As shown in Table 3.9 it is RCC Central section with over flow stepped spillway and zoned earth fill wing embankments. The objectives of the dam are for Industrial supply, irrigation and recharge.

Figure 3.22: Al-Walah dam

Table 3.9: Al-Walah dam specification (Jordan Valley Authority, 2015)

Location	On Wadi Wala,60 km south of Amman
Construction	Construction completed in 2002
Type	RCC Central section with over flow stepped spillway and zoned Earth fill Wing embankments
Height	52 m
Storage capacity	9.3 MCM
Purpose	Industrial supply and irrigation and Recharge

Al-Walah dam is situated in a terrain which has excellent potential to construct PHES system. One candidate location as shown in Figure 3.23, which has a proper height difference is found to be 131 m, and has enough suitable area where the upper reservoir can be constructed.

Figure 3.23: Candidate location in Al-Walah dam

The candidate location in the dam area is close to the electric grid. This is advantageous regarding the construction cost (i.e, reducing the electrical transmission cost). Figure 3.24 indicates that the distance between the upper and lower storage is approximately 550 m which is acceptable from design point of view. The elevation of upper storage is found to be 646 m above the sea level, whereas the powerhouse location height is 515 m near the end of the hill.

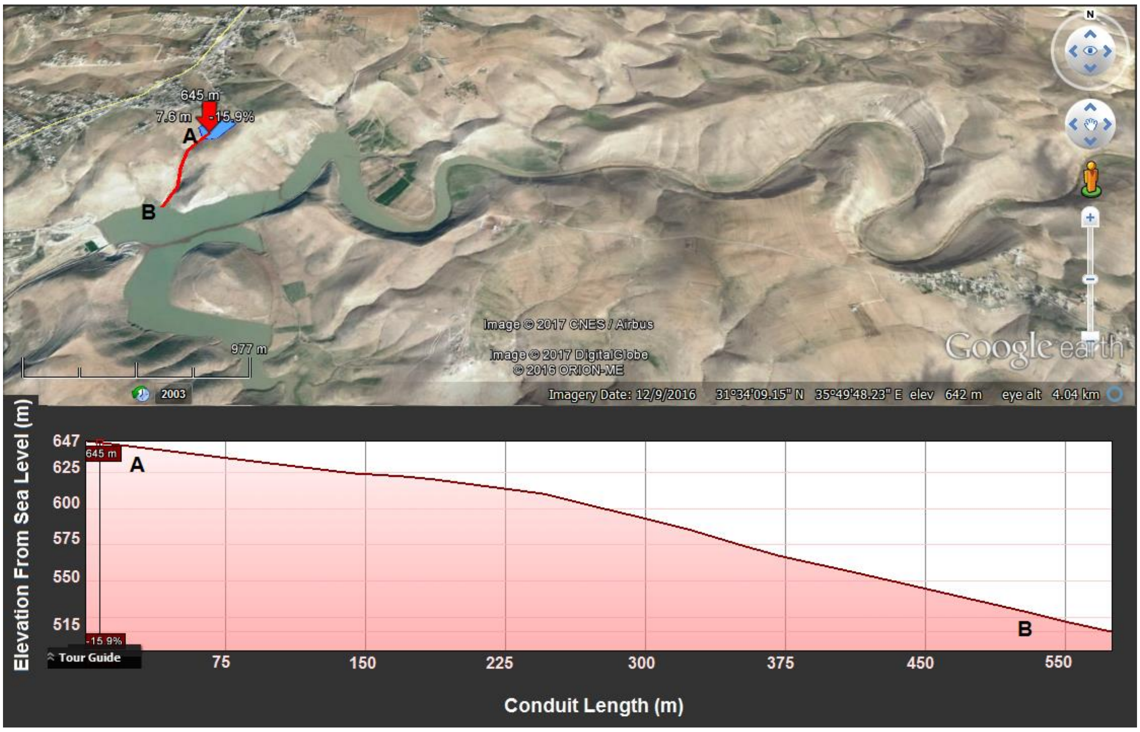

Figure 3.24: The curve in the bottom graph shows the Elevation difference profile between the points A and B marked in the picture of Al-Walah dam

The same method will be conducted to estimate the amount of electrical energy that can be stored in the proposed PHES system at Al-Wala dam. It is important to examine the water balance for the dam, including the storage volume, inflow and outflow rate for at least 3 years to find out if water level is available all through a year that will make the PHES work in a sufficient way. As in Table 3.9 the capacity storage of Al-Walah dam is 9.3 MCM. Figure 3.25 Shows the water balance through the period from 2011 to 2017. The minimum value of storage volume through this period was about 1.2 MCM in 9/1/2012.

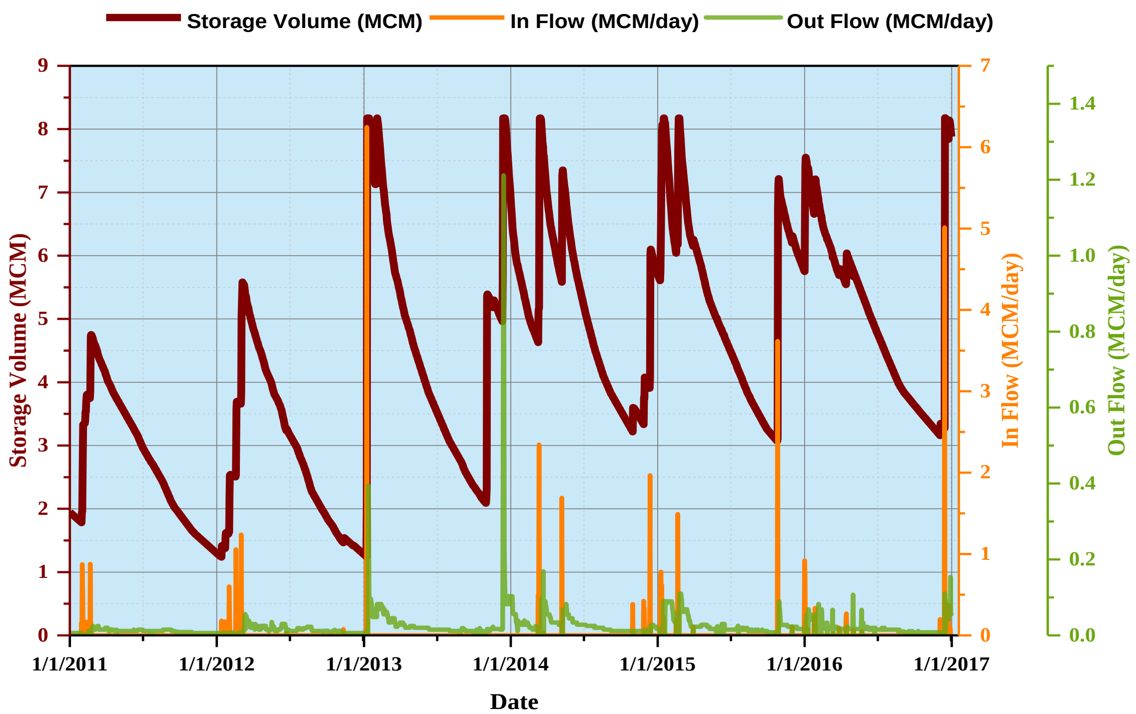

Figure 3.25: Water balance for Al-Walah dam

As in the previous procedure in section 3.3, the rated pumping head at the proposed site is 131 m ,by using equation 3.1, the rated discharge from the pump at rated head and 1 MW pumping power is calculated to be $0.7\, m^3/s$. Assume the pump will be continuously operated for 12 hours, by using equation 3.2, the required volume of upper storage is $30.2{\times}10^3\ m^3$.

Now it is easy to expand the system capacity by multiply the required rated pump power by the volume of upper storage that was used to store water for only 1MW rated pumping power for 12 hours. If the capacity is considered to be 50 MW then the volume of the upper reservoir that is needed is 1.5 MCM. Which is 125% of the minimum stored volume that Al-Walah dam has reached in 9/1/2012. To solve this issue there are two ways: the first is by reducing the full working hours of the storage system, the second which is recommended, by increasing the dead limit volume value of the dam. If the working hours is reduced to be 6 hours, then the required volume is 0.7 MCM which is approximately 58 % of the minimum stored volume. As shown in Table 3.10 the area of the location is $40 \times 10^3 m^2$, some excavation at the site is required to get the depth of 18 m that is needed for designed volume of 0.7 MCM that can store 300 MWh daily.

Table 3.10**:** The specification of the candidate sites in Al-Walah dam

The candidate places	Latitude & longitude	Projected Area (m^2)	Depth (m)	Height difference(m)
Location 1	31°34'29.05"N 35°48'31.27"E	40000	Dependent on the capacity	646-515=131

Figure 3.26 indicates the relation between the expected daily energy that can be stored in Al-Walah dam and the volume of the upper reservoir which is needed to store this amount of electrical energy. It also shows the percentage of upper reservoir volume to the minimum storage volume level in the existing lower reservoir (dam).

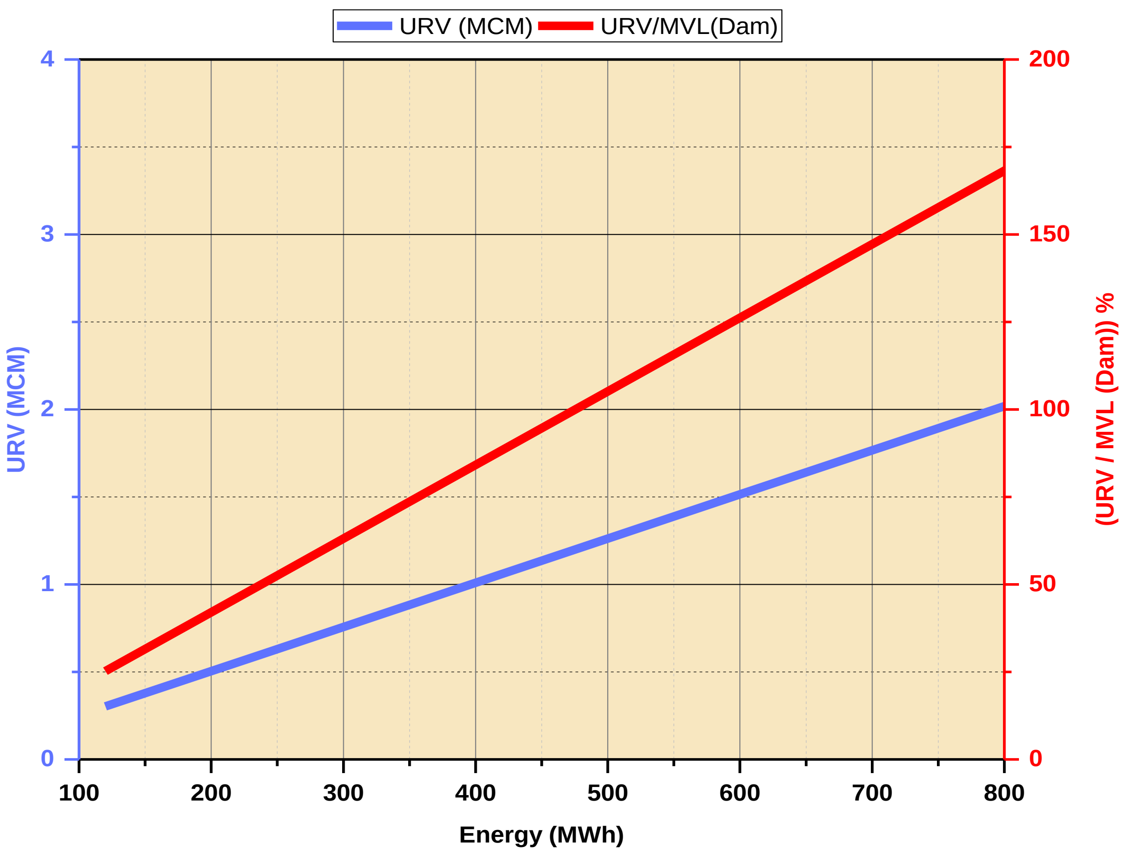

Figure 3.26: Expected daily energy in Al-Walah dam with respect to the Upper Reservoir Volume (URV) and the ratio of URV with the Minimum Volume Level (MVL) of existing lower reservoir (dam)

3.4.6 Al-Tannur Dam

Altannur dam as shown in Figure 3.27 is located in Tafila government south of Jordan, at Wadi AL Hissa. The construction was started in 1999 and completed in 2001. As indicated in Table 3.11 it is RCC with overflow stepped spillway. The main Purpose of the dam is for Irrigation.

Figure 3.27: Al-Tannur dam

Table 3.11: Al-Tannur dam specification (Jordan Valley Authority, 2015)

Location	On Wadi Hissa,175 km south of Amman
Construction	Construction completed in 2001
Type	RCC with overflow stepped spillway
Height	60 m

Storage capacity	16.8 MCM
Purpose	Irrigation

Al-Tannur dam has a good potential to construct PHES system. As shown in Figure 3.28 two candidate locations are identified which have proper height difference that ranges from 340 to 350 m and have enough suitable area where the upper reservoir can be constructed.

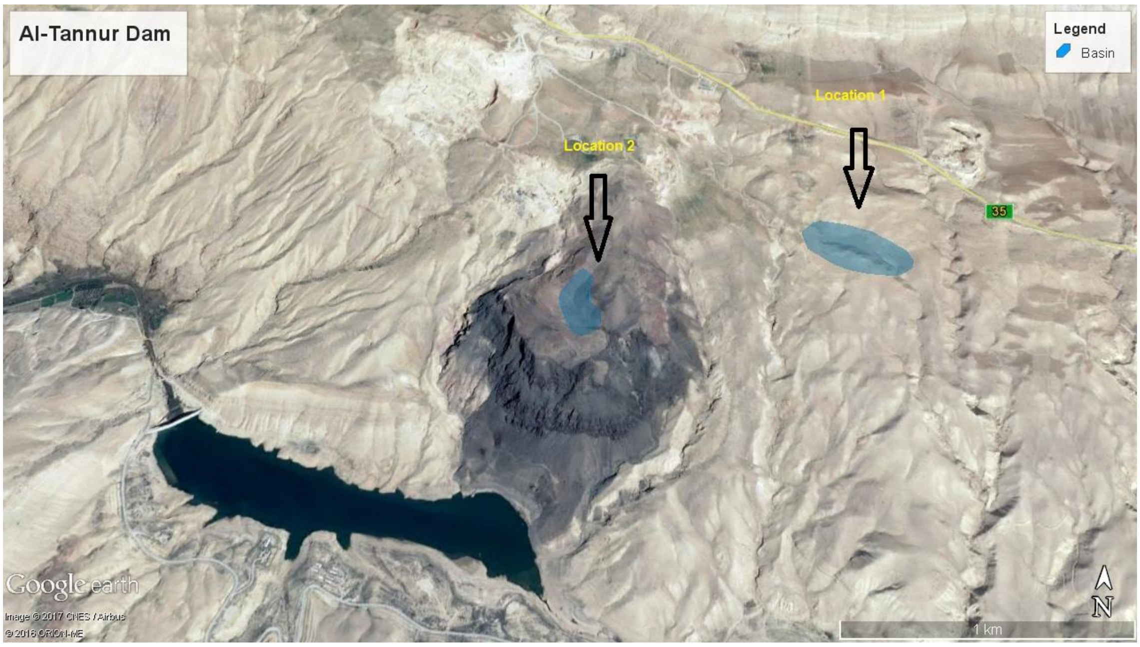

Figure 3.28: Candidate locations in Al-Tannur dam

The second location situated in basalt mountain and it is a natural basin. The candidate locations in the dam area are close to the electric grid. This is an advantageous regarding the construction cost, (i.e, reducing the electrical transmission cost). Figure 3.29 indicates that the distance between the upper and lower storages for the first location is approximately 1.5 km. which is acceptable from design point of view. The elevation of upper storage is found to be 739 m above the sea level, whereas the powerhouse location height is 390 m near the end of the hill.

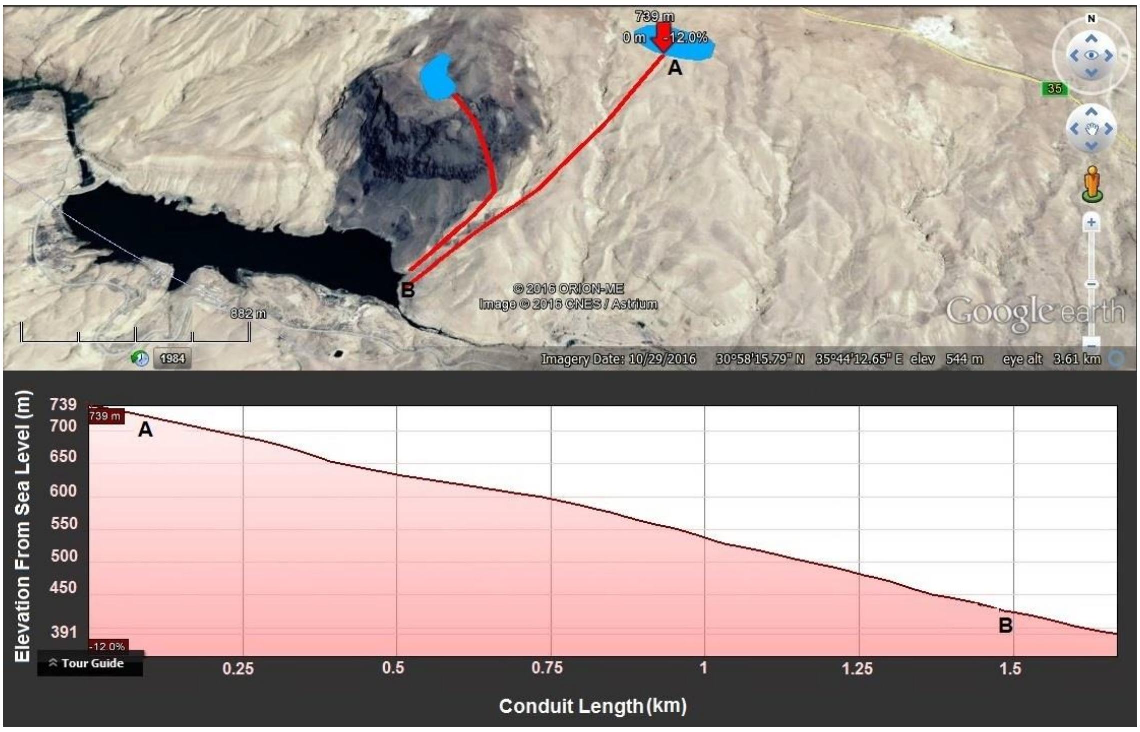

Figure 3.29: The curve in the bottom graph shows the Elevation difference profile between the points A and B marked in the picture of Al-Tannur dam

The same method will be conducted to estimate the amount of electrical energy that can be stored in the proposed PHES system at Al-Tannur dam. It is important to examine the water balance for the dam, including the storage volume, inflow and outflow rate for at least 3 years to find out if water level is available all through a year that will make the PHES work in a sufficient way. As in Table 3.11 the capacity storage of Al-Tannur dam is 16.8 MCM. Figure 3.30 shows the water balance through the period from 2011 to 2017. The minimum value of storage volume through this period was about 1.9 MCM in 2/1/2013.

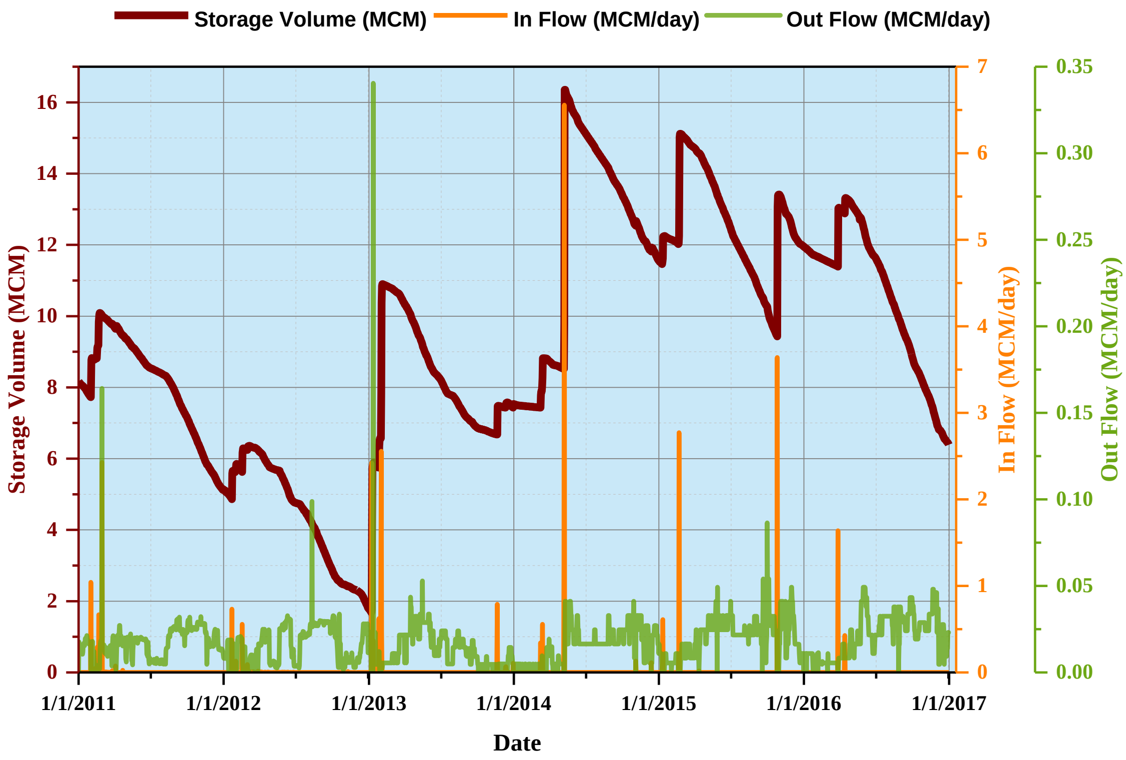

Figure 3.30: Water balance for Al-Tannur dam

Following the procedure in section 3.3, the rated pumping head at the proposed site is found to be 349 m, by using equation 3.1, the rated discharge from the pump at rated head and 1 MW pumping power is calculated to be 0.265 m^3/s .Assume the pump will be continuously operated for 12 hours, by using equation 3.2 the required volume of the upper storage is $11.3\times10^3\ m^3$.

To expand the system capacity, multiply the required rated pump power by the volume of upper storage that was used to store water for only 1MW rated pumping power for 12 hours. Assume the capacity is set to be 100 MW, then the volume of the upper reservoir that is needed is 1.1 MCM. Which is 57.8% of a minimum storage volume that Al-Tannur dam has reached in 3/1/2013. As shown in Table 3.12 the area of first location is found to be $96\times10^3 m^2$, additional miner work at the site is required to get the depth of 11.4 m that is needed for designed volume of 1.1 MCM that can store 1200 MWh daily.

Table 3.12: The specification of the candidate sites in Al-Tannur dam

The candidate places	Latitude & longitude	Projected Area (m^2)	Depth (m)	Height difference(m)
Location 1	30°58'42.53"N 35°44'32.49"E	96000	Dependent on the capacity	739-390
Location 2	30°58'30.75"N 35°43'50.66"E	31000	Dependent on the capacity	710-390

Figure 3.31 indicates the relation between the expected daily energy that can be stored in Al-Tannur dam and the volume of upper reservoir which is needed to store this amount of electrical energy. It also shows the percentage of upper reservoir volume to the minimum storage volume level in the existing lower reservoir (dam).

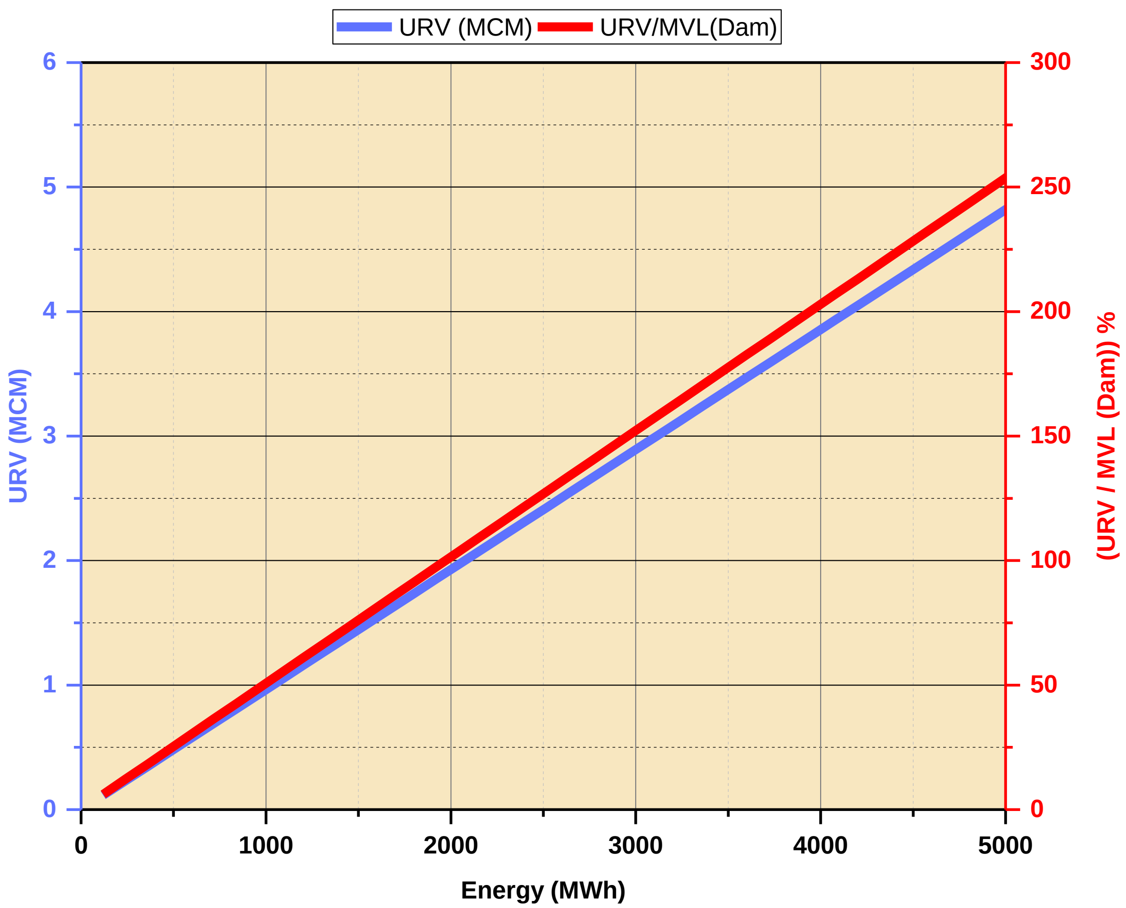

Figure 3.31: Expected daily energy in Al-Tannur dam with respect to the Upper Reservoir Volume (URV) and the ratio of URV with the Minimum Volume Level (MVL) of existing lower reservoir (dam)

3.5 Future plan

Nowadays, Jordan has a mini hydro power station in King Talal dam with a 5 MW rated capacity which is implemented by the National Electric Power Company. According to Jordan valley authority, Jordan is constantly trying to promote an alternative solution to generate electrical energy utilizing the dams and their expansions in the future. Jordan Valley Authority will conduct a number of studies for the possibility of generating electricity from the existing dams such as Al-Mujib, Al-Tanour , Al-Walah and Wadi Al-Arab dams. These projects can save the environment, and keep it clean from pollution. It will also open new job oppourtinties in these future power plants once it is completed. There is a strategic plan to raise the main storage capacity of the dams to 400 MCM by 2020. A number of dams have been implemented such as Wadi Kufranja dam in Ajloun, Ibn Hammad in Karak, Wadi Al- Karak, Lajjun, and Zarqa Ma'in dam. These can enhance the elictcity generation in Jordan.

3.6 Poor opportunity sites

Some dams in Jordan do not have the minimum requirements to establish energy storage system which are the height difference, available volume of water, and suitable area to construct upper storage. These sites include: Ziglab, Karamah, Shuaib and Kafrein dams. Table 3.13 shows the specification for each dam.

Table 3.13: Poor opportunity sites

Dam	Location	Construction	Type	Height	Storage capacity
Wadi Shuib	At Wadi Shuib	Construction Completed in 1969	Earth –fill	32 m	1.4 MCM
Kafrein	At Wadi Kafrein	Completed in 1967, raised in 1997	Earth –fill	37 m	8.4 MCM
Ziglabe	At Wadi Ziglab	Construction Completed in 1967	Earth –fill	48 m	3.9 MCM
Al-Karamah	At Wadi mallaha	Construction Completed in 1997	Earth –fill	45 m	53 MCM

As shown in Figure 3.32 The water balance for Ziglab, Shuaib and Kafrein dams indicates that they don’t have suitable volume storage and also, they frequently reach the least amount level of storage capacity.

As shown in Table 3.13 Al-Karamah dam has large storage capacity. Figure 3.33 shows the water balance analysis for Al-Karamah dam which indicates that it has good potential volume storage but the nearby terrain does not have suitable height difference as shown in Figure 3.34 the terrain around the dam almost has similar elevation.

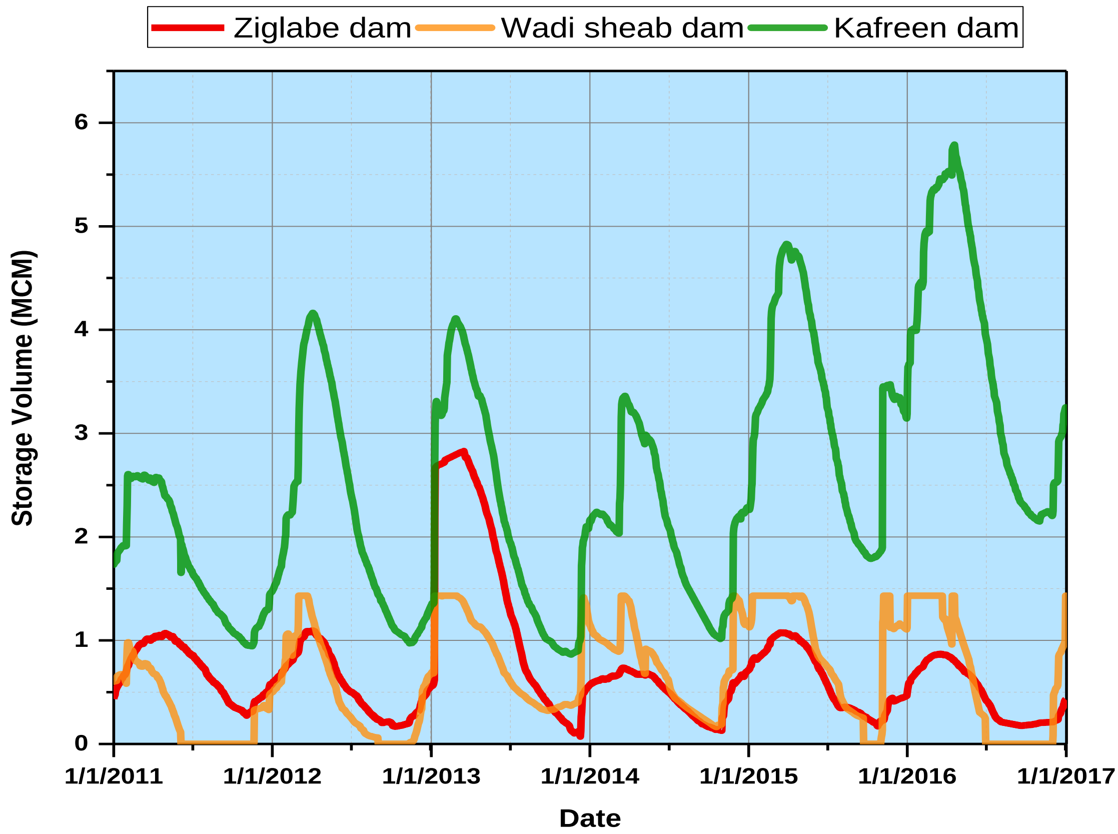

Figure 3.32: Water balance for Ziglab, Wadi Shuib and Kafrein dams

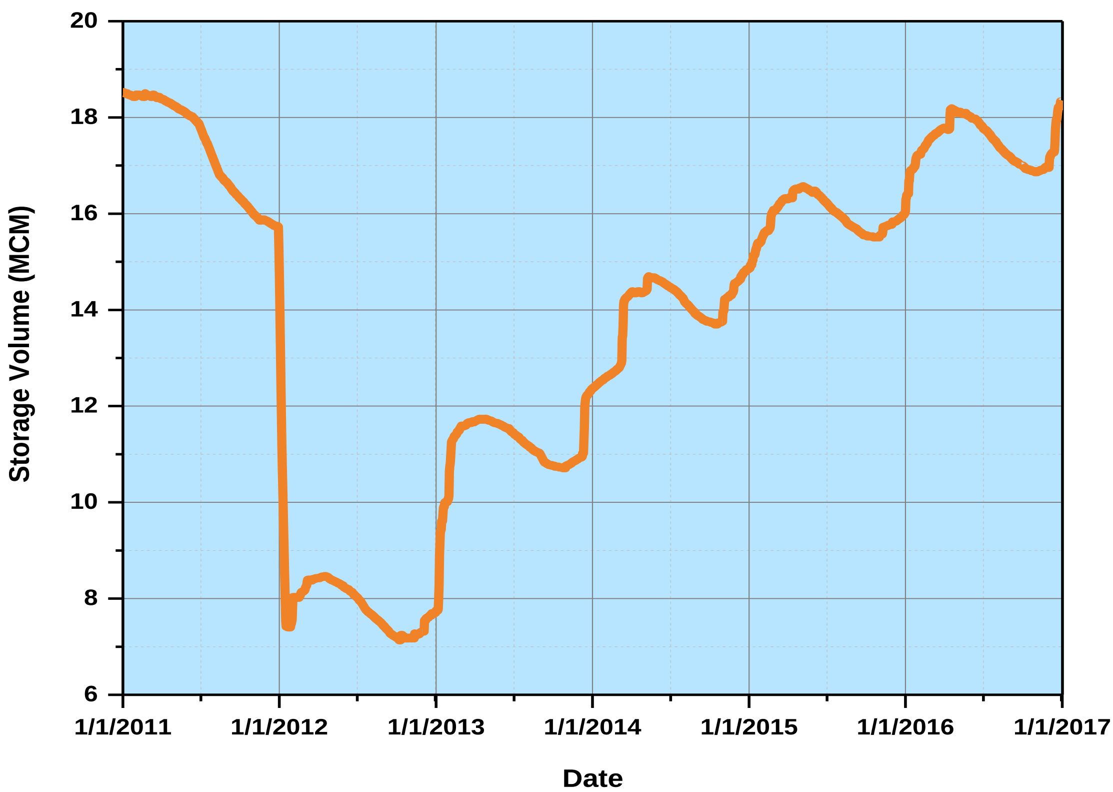

Figure 3.33: Water balance for Al-Karamah dam

Figure 3.34: Al-Karamah dam

3.7 Chapter summary

Ten dams have been analyzed by studying the geographical nature of the terrain nearby the dam. Also, a water balance for each dam has been studied to ensure that the water volume is always available when the dam drawn to minimum level. Table 3.14 shows a summary of the feasible and not feasible sites according to the achievement of design requirements of PHES system.

King Talal, Al-Wehdah, Wadi Al-Arab, Al-Tannur, Al-Mujib and Al-Walah dam, they all have achieved the basic requirements to install PHES. Al-Karamah, Ziglab, Shuib, and Al-Kafrien dam, none of them has met the basic requirements to install PHES due to the minimum available water value and the height difference are relatively small.

Table 3.14: Sites summary

Dam	Location	Storage capacity (MCM)	Feasible	Not Feasible
King Talal	Zarqa valley	74	✓	
Al-Tannur	Wadi Hissa	16.8	✓	
Al-Wehdah	Yarmouk River	115	✓	
Wadi Al-Arab	Wadi Al-Arab	16.8	✓	
Al-Mujib	Wadi Mujib	31.2	✓	
Al-Walah	Wadi Walah	9.3	✓	
Wadi Shuib	Wadi Shuib	1.4		✓
Kafrein	Wadi Kafrein	8.4		✓
Ziglabe	Wadi Ziglab	3.9		✓
Al-Karamah	Wadi mallaha	53		✓

Chapter Four

Design of a pumped hydro electrical energy storage

4.1 Introduction

PHES systems provide necessary support to the electricity grid, assisting to balance the movement of power across the transmission networks by absorbing unwanted energy when electricity demand is low and releasing it when the demand is high. With an ability to respond almost immediately to variations in the amount of electricity flowing through the grid. Pumped storage is a vital part of the nation's power network. PHES systems are a reliable grid-scale energy storage technologies which can furthermore enable the countries to develop its renewable energy sector. In PHES systems, electric energy is converted into hydraulic potential energy that can be stored until it is needed then reconverted into electricity. PHES systems are recognized by reversible pumping/generation modes, made possible by a hydroelectric generating set comprising a turbine, a generator, and an electric pump. In pumping mode, electricity is used to pump the water into the upper reservoir. In generation mode, the water is released into the bottom reservoir and passes through turbines which are attached to electric generators ("Pumped Storage | National Hydropower Association,"2013.).

4.2 Types of PHES

There are two major types of PHES systems as following:

1. Essential PHES system which depends totally on the water pumped into an upper water reservoir as their means of storing energy.

2. Combined PHES, also known as pump-back power plants, utilizes a combination of pumped water and natural stream flow to store/release energy (Namgyel, 2012).

4.3 Configurations of PHES

There are three main configurations of PHES:

1- Four units: A separate pump coupled to a motor and a turbine coupled to a generator. This configuration occupies a significant amount of space and is no longer used.

2-Three units: A pump and turbine are both coupled to a single reversible motor/generator. The efficiencies of the pump and turbine can be optimized, and multi-stage pumps can be used for very high heads.

3- Two units: A reversible pump/turbine is coupled to a reversible motor/generator. This configuration takes up a smaller space compared to the other two and has a lower installation cost. However, the disadvantage is, it has relatively lower efficiency compared to other configurations. More than 95% of the PHES today in the world are of this type (Namgyel, 2012).

The PHES system turnaround/cycle efficiency is defined as the ratio between the energy supplied while generating and the energy consumed while pumping. This efficiency depends on both the pumping efficiency (η_p) and the generation efficiency (η_g). The turnaround efficiency of any PHES system (η) is given as the product of pumping efficiency and generation efficiency i.e.

$$\eta = \eta_p \times \eta_g \tag{4.1}$$

The turnaround efficiency usually ranges between 70-85%. PHES can be brought online within 90 seconds and can be functioning at full power within 120 seconds. It can also switch from pumping to generation or from generation to pumping mode in 180 to 240 seconds.

4.4 Classifications of turbines

Turbines are used for converting hydraulic energy into mechanical energy. The hydraulic turbines are classified into two types, impulse and reaction. In impulse turbines, there is no pressure drop across the moving blades, whereas in reaction turbines the pressure drop is divided in the guide vanes and moving blades. The reaction turbines are low head high flow rate machines. For reaction turbines, the rotor is surrounded by a casing (or volute), which is completely filled with the working fluid. Turbines are manufactured in a variety of configurations, radical flow, axial flow and mixed flow. Typical radial and mixed flow hydraulic turbine is Francis turbine (Hussian, Abdullah, & Alimuddin, 2008).

4.4.1 Francis turbine

Francis turbine is suitable for medium head and medium discharge. It exists in large numbers throughout the world. It is applied at head ranges generally from about 20 to 750 meters and in power ranges from about 0.25 to 800 MW per unit. It is classified as a reaction turbine which operates under hydraulic pressure energy and part of kinetic energy. The flow is radial, and it is contained in a spiral casing called volute that channels the water into the runner. The volute has a decreasing area to maintain uniform velocity, towards the row of stationary vanes. A sketch of a Francis turbine is shown in Figure 4.1.

In the Francis turbines two effects cause the energy transfer from the flow to the mechanical energy on the turbine shaft: Firstly, it flows from a drop-in pressure from inlet to outlet of the runner. This is denoted as the reaction part of the energy conversion. Secondly, the changes in the directions of the flow velocity vectors through the runner blade channels transfer impulse forces. This is denoted as the impulse part of the energy conversion (Hussian et al., 2008).

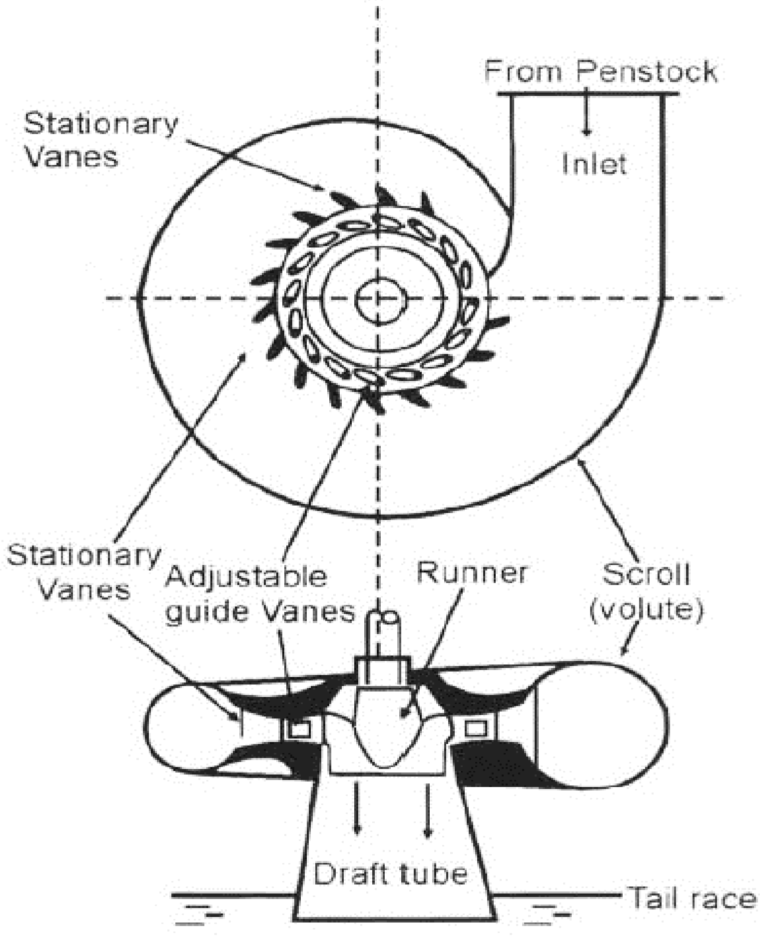

Figure 4.1: Francis turbine (Hussian et al., 2008)

4.4.2 Pelton turbine

Pelton is a high head turbine which is classified as an impulse turbine since there is no pressure drop across the buckets. The flow is axial. Water supplied is from a high head through a long conduit called penstock. The water is accelerated in the nozzle, and the head is converted into velocity and discharges at high speed in the form of a jet at atmospheric pressure. The jet strikes deflecting buckets attached to the rim of a rotating wheel (runner) as shown in Figure 4.2 (Hussian et al., 2008).

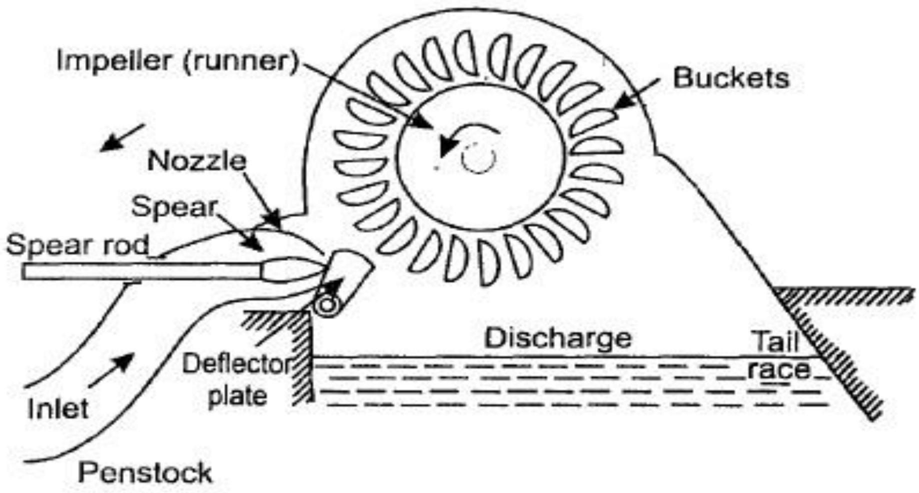

Figure 4.2: Pelton turbine (Hussian et al., 2008)

4.4.3 Kaplan turbine

Kaplan is a low head, reaction turbine. The flow is axial. In Kaplan turbine, both the guide vanes and runner blades are adjustable with load thus maintaining high efficiency.

4.5 Turbine selection for case study

At the outset of the design process, some overall requirements of the machine should be known. For a hydraulic turbine, these would include the head required H, the volumetric flow rate Q, and the rotational speed N.

Figure 4.3 illustrates the relation between the total head H (m) with the flow rate Q (m^3/s) and power capacity P (MW) of the main hydraulic turbine**s**. In this work, the capacity for each set P= 75 MW, Q = 24.3(m^3/s), and the rated head H = 349 m. It is obvious that Francis will work efficiently. But this is not enough to make the decision.

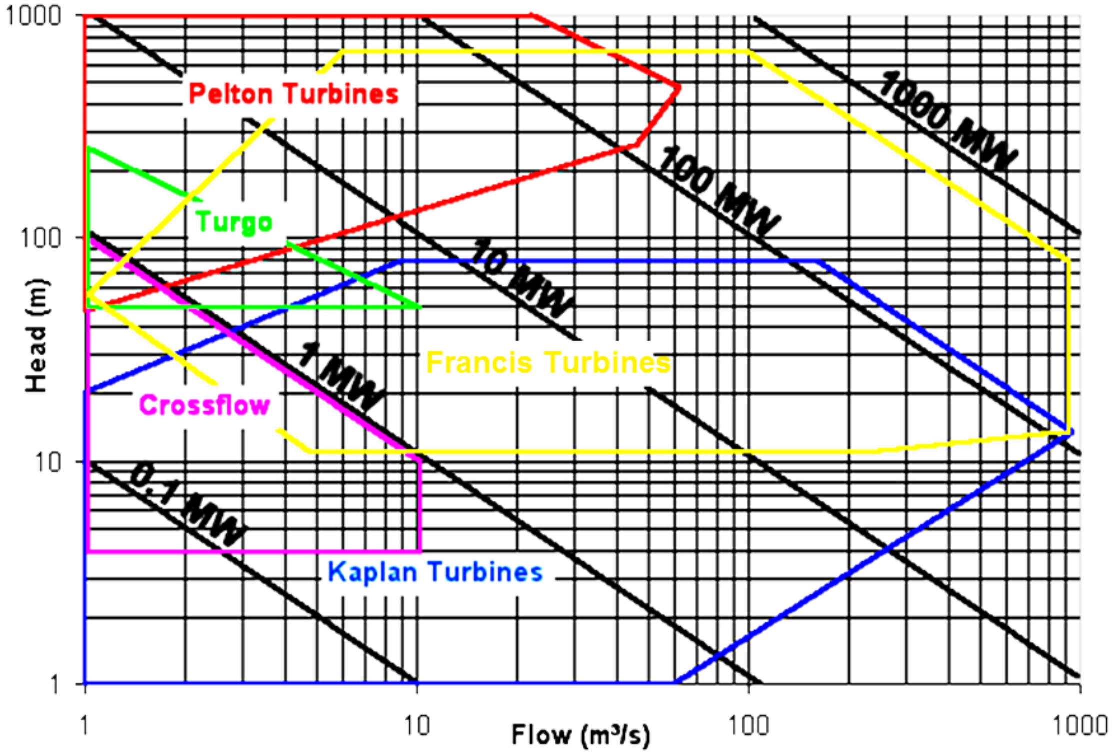

Figure 4.3: Power capacity P (MW) of the main hydraulic turbines with head (m)

A non-dimensional parameter called the specific speed Ns is often used to decide upon the choice of the most appropriate machine. The value of Ns gives the designer a guide to the type of machine that will provide the normal requirement of high efficiency at the design condition. It can be calculated by using equation 4.2.

$$Ns = \frac{N \times P^{\frac{1}{2}}}{H^{\frac{5}{4}}} \tag{4.2}$$

Where: H is the head in ft, P the power output in hp, and N the speed in rev/min of runner.

In this work where P = 75 MW ($100.5\times10^3\ hp$), H =349 m (1145 ft), then N (RPM) can be obtained from Figure 4.4 which is a selection chart for Francis turbines that gives the relation between head (m), flow (m^3/s), power (MW), penstock diameter (m) and runner speed N (RPM). After matching the values of H, P and Q in the chart, the appropriate inlet diameter is 1.85 m and runner speed is found to be 600 RPM.

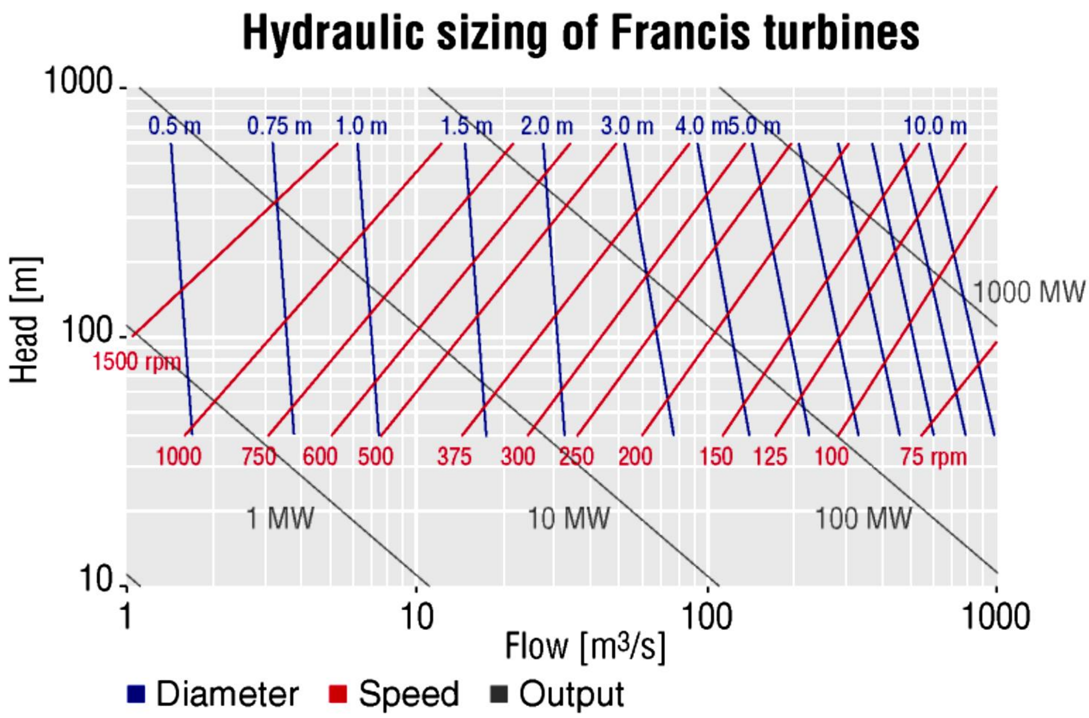

Figure 4.4: Selection chart for Francis turbines (Meier, 2011)

It is possible now to calculate Ns by substituting N, P, and H in equation 4.2:

$$Ns = \frac{N \times P^{\frac{1}{2}}}{H^{\frac{5}{4}}} = \frac{600 \times (100.5 \times 10^3)^{\frac{1}{2}}}{1145^{\frac{5}{4}}} = 28.5$$

Figure 4.5 shows the ranges of specific speed appropriate to different types of hydraulic turbines. As shown the range of Ns for Francis turbine is from (20-100). Therefore, Francis will be the appropriate turbine for this project.

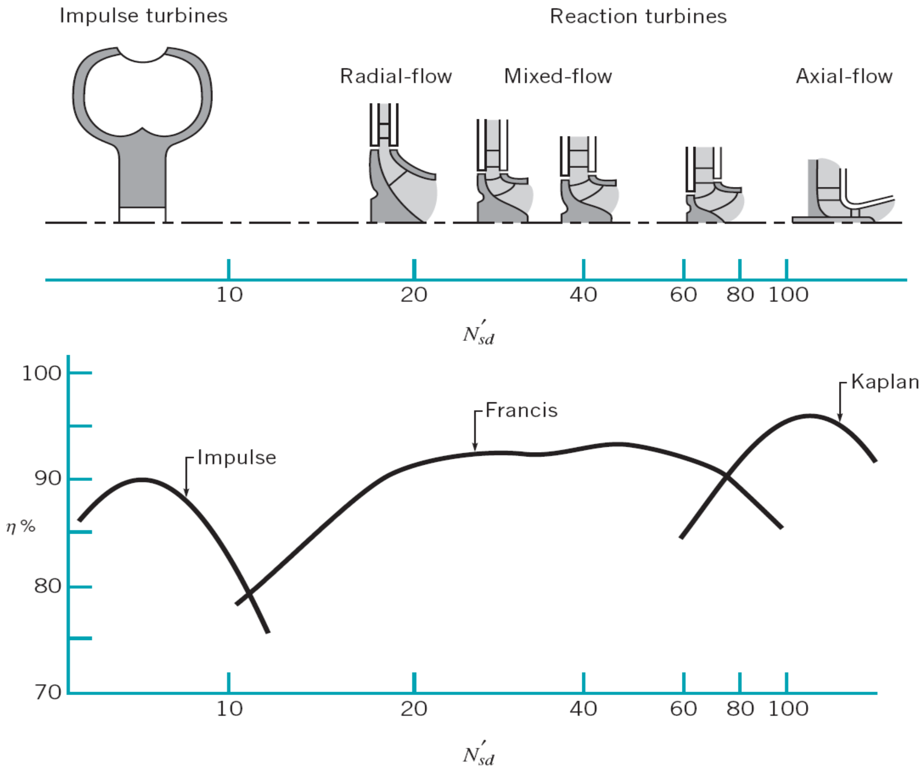

Figure 4.5: Typical turbine cross sections and maximum efficiencies as a function of specific speed ("Turbines," 2008.)

4.6 Identification of PHES site for case study in Jordan

Not only Al- Tannur dam has all the characteristics discussed in Chapter Three Section 3.2, but also it is located close to the wind farms in the southern region and also fulfills the geographical requirements of PHES constructions (see chapter three section 3.4.6). This makes it the best candidate site as a case study to design PHES system in this research. Figure 4.6 shows the topography map for the proposed site where the storage system will be constructed, which includes the system components: upper reservoir, power house, and lower reservoir.

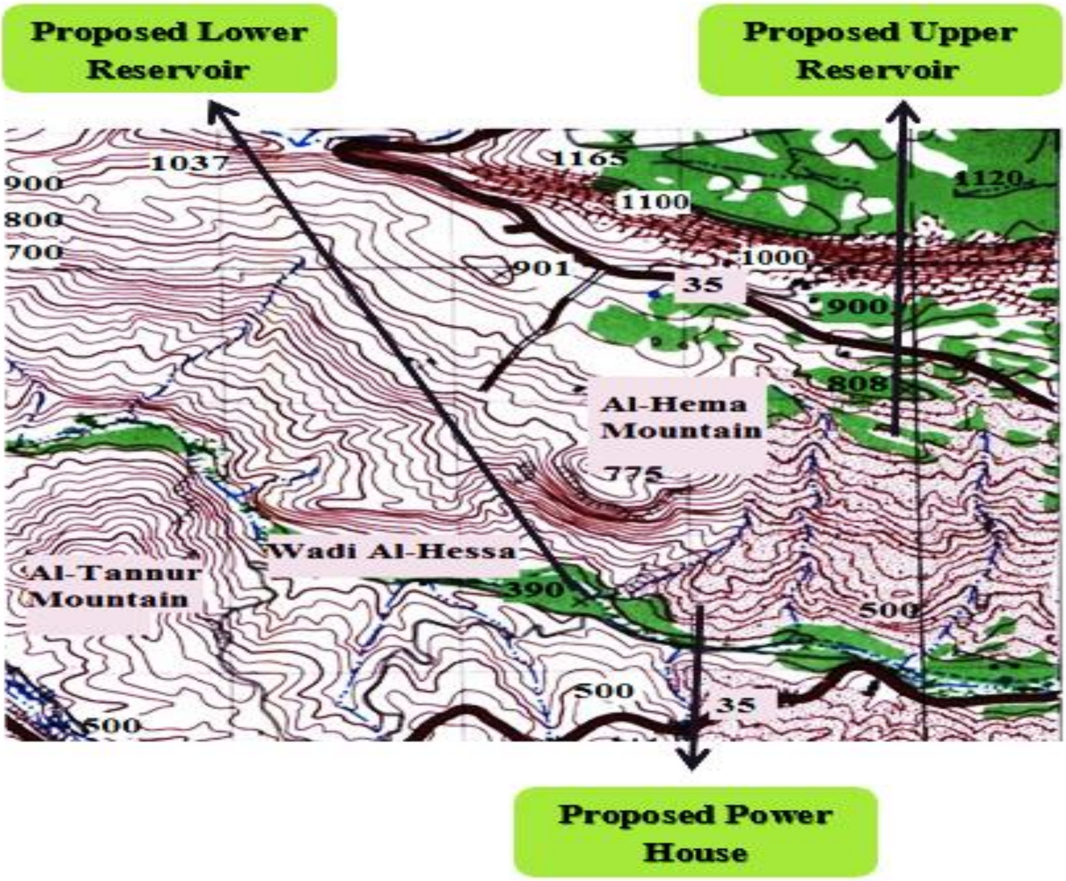

Figure 4.6: Topography map for the proposed site

4.7 Specifications of storage system's components

The storage system consists of four components: upper reservoir, lower reservoir, power house and conduit.

4.7.1 Upper reservoir

As indicated in Figure 4 .6, the proposed upper reservoir will be towards the top right of Al-Hima mountain. The mountain has a crest of 770 m with a suitable storage contour at 739 m. The surface area has a length of 600 m and a width of 220 m. The area of the upper reservoir that is available is $96{\times}10^3 m^2$ with a dimensions of length 480 m and width 200 m. Figure 4.7, Figure 4.8 and Figure 4.9 show the elevation profile of three different paths at the proposed site of the upper reservoir which indicates that the site will need additional miner work on the terrain surface and the upper reservoir can be constructed at the lowest cost to reach a depth of 16 m to obtain the gross storage capacity of 1 .54 MCM. To prevent the leak of water from the reservoir through seepage, a lining is also required.

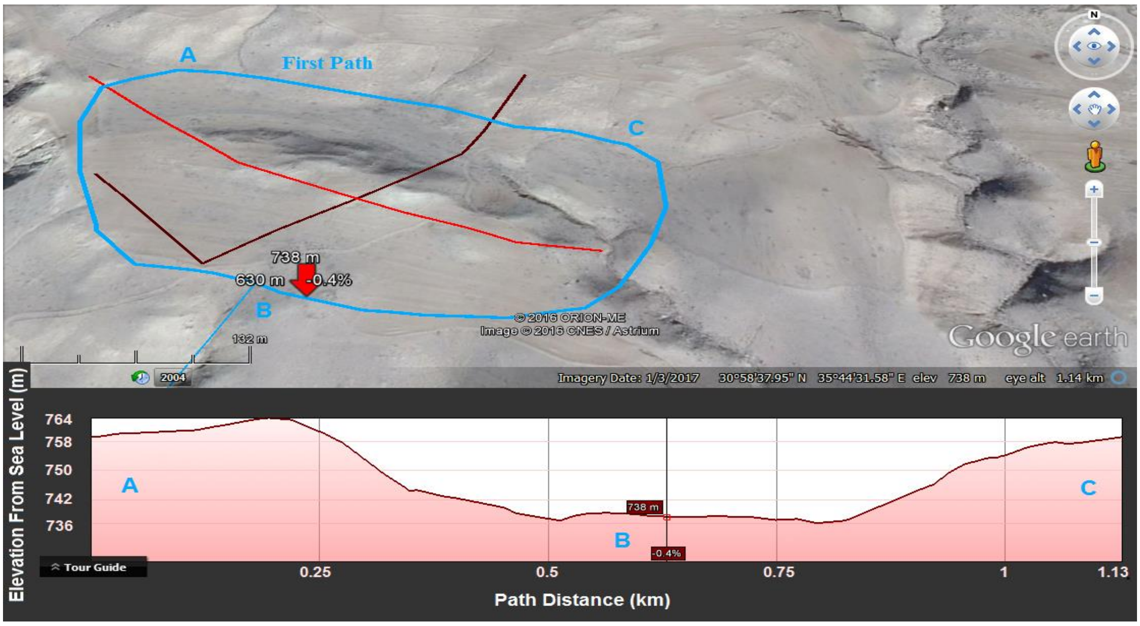

Figure 4.7: Elevation profile of first path (blue line)

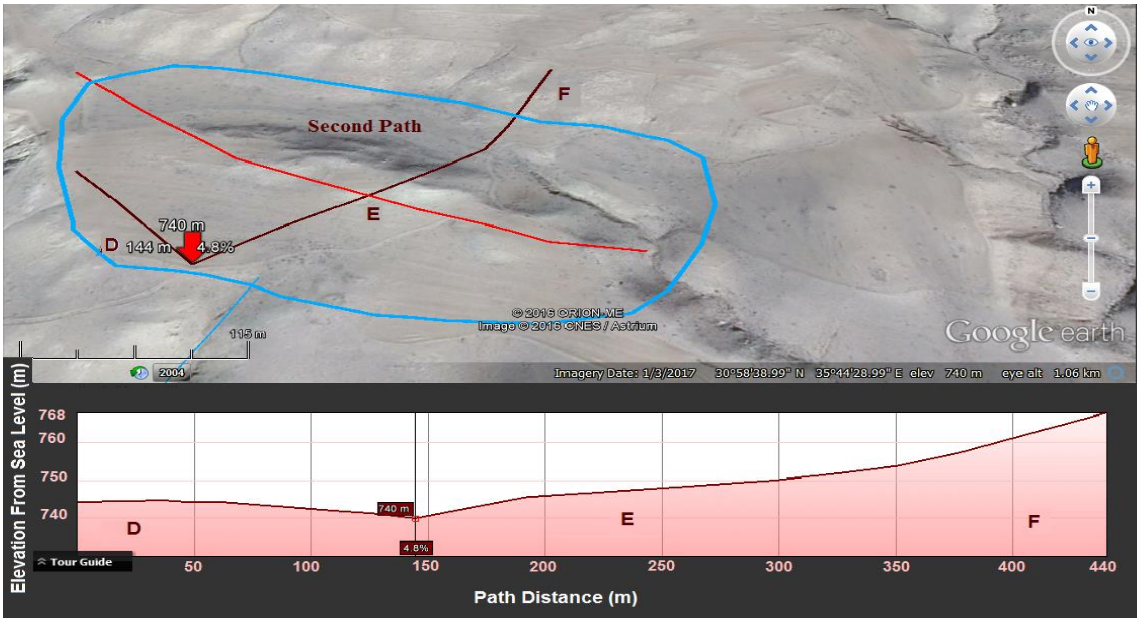

Figure 4.8: Elevation profile of second path (brown line)

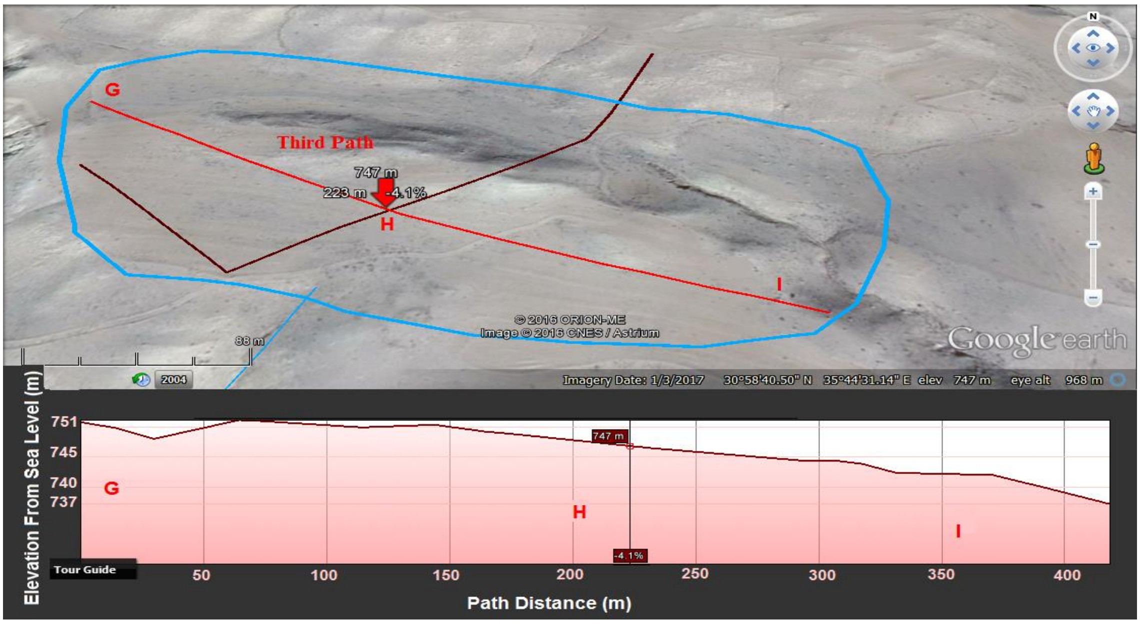

Figure 4.9: Elevation profile of third path (red line)

4.7.2 Lower reservoir

As shown in Figure 4.10, Al-Tannur dam is the lower reservoir of PHES that is located at the end of Al-Hima Mountain at elevation of 390 m above sea level (see chapter three section 3.4.6). So, Al-Tannur dam will serve as the lower reservoir. This is a great economic benefit of the PHES site as the lower reservoir involves very little construction.

Figure 4.10: Lower reservoir

4.7.3 Power House

The power house would be located towards the end of the water conduit near the lower reservoir. The power output of the reversible pump-turbine is expressed by the following set of equations, where the symbols are defined after each equation.

Rated power output from generator**:**

$$P_g = \rho \times g \times h \times Q_g \times \eta_g \tag{4.3}$$

Where:

P_g: Rated generator Power (W).

Q_g: Rated volume flow rate (m^3/s).

η_g: Generator efficiency.

g: Acceleration of gravity $(9.8\, m/s^2)$.

ρ: Density of water $(1000\, kg/m^3)$.

As mentioned before the suitable area of the upper storage has a contour at 739 m above sea level and the minimum water level is set to be 2 m so the minimum draw down level of the upper reservoir is 725 m (739 m-14 m) above sea level, and therefore the minimum head is 335 m and the rated head is 349 m. The effective storage of the upper reservoir that can be used to generate electricity is therefore 1.34 MCM (i.e. 480 x 200 x 14). It is proposed to install two reversible pump-turbine sets with a rated capacity of 75 MW for each set. By using equation 4.3, the rated discharge from each turbine at rated head, rated power output and generator efficiency of 0.9 can be calculated to be

24.36 m^3/s. The upper reservoir has the storage capacity to generate rated power output continuously for 7.7 hours.

In pumping mode, the power required to pump the rated discharge into the upper reservoir is given by:

$$P_P = \frac{\rho \times g \times h \times Q_P}{\eta_P} \tag{4.4}$$

Where:

P_P: Rated Pump Power (W).

Q_P: Rated volume flow rate (m^3/s).

η_P: Pump efficiency.

g: Acceleration of gravity $(9.8\, m/s^2)$.

ρ: Density of water $(1000\, Kg/m^3)$.

It is assumed that the water level in the lower reservoir is always maintained at 390 m above sea level. Using equation (4.4), the water that can be pumped into the upper reservoir from the lower reservoir at rated capacity P = 75 MW, average head of 342 m and assuming pump efficiency of 0.9 is 20.1 m^3/s. The pumps can be operated continuously for 9.3 hours. Table 4.1 shows the characteristics of the proposed PHES system in Al-Tannur dam.

Table 4.1: The station characteristics of the proposed PHES system

Machine type	Reversible pump-turbine unit (Francis)
Overall capacity	150 MW
Capacity of each unit	75 MW
Units number	2 units
Rated head	349 m
Minimum head	335 m
Average head	342 m
Generator efficiency	90%
Pump efficiency	90%
Overall efficiency	81%
Rated discharge of generator mode	24.36 (m^3/s) For each unit
Rated discharge of pump mode	20.1 (m^3/s) For each unit

4.7.4 Conduit

It is a group of pipes connected with each other extending from the upper reservoir to the lower reservoir. the total length of water conduit connecting the lower reservoir through the pump-turbine to the upper reservoir is 1500 m. Therefore, L:H ratio is calculated to be 4.29 (1500/349), which is within the acceptable range from design point of view. A number of fitting will be required (i.e. elbow fitting, entrance to pipe fitting, exit to container fitting) that may increase the friction losses through the piping system.

4.8 Piping design

It is important to maintain fluid velocities to approximately 7 m/s, through all piping connection joints. This is recommended for many reasons (“Hydraulics,” n.d.):

1- Friction Loss: Higher fluid velocities increase friction losses (frequently known as “pressure drop”), leading to increased pump energy costs.
2- Noise and Vibration: High velocities can lead to increased vibration and noise.
3- Erosion / Corrosion: Fluids have a greater propensity to damage the inside walls of pipe at high velocities.
4- Hydraulic Shock: Also, known as “water hammer”. Hydraulic shock can cause excessive damage when a line is shut down suddenly. Maintaining a low fluid velocity will substantially reduce the impact of the hydraulic shock.
5- Very high velocity (i. e. more than 10 m/s) can also cause significant cavitation problem as air bubbles are formed from low water pressure, and they would collapse when entering a region of high water pressure.

4.8.1 Pipe diameter calculation

As mentioned above it is important to calculate the appropriate diameter of the piping system, to maintain a volume flow-rate velocity within the accepted range. Its value can be calculated as following:

1- Identify the designed velocity v (m/s) of the rated volume flow-rate.
2- Identify the rated volume flow-rate.
3- Use following formula to calculate the section area of the pipe.

$$A = \frac{Q}{v} \tag{4.5}$$

Where: A = section area m^2 ,Q = volume flow-rate m^3/s, v = velocity m/s.

4- Since the pipe has a circular area, the appropriate diameter can be obtained by using following equation.

$$A = \pi \times \frac{d^2}{4} \tag{4.6}$$

For pumping mode, the designed velocity is set to be 5.8 m/s, and the rated flow-rate Q is 20.1 m^3/s. After following the previous procedure, the diameter of piping system is found to be 2.1 m.

In generation mode, volume flow rate is higher than in pumping mode, having the same diameter in both situations which is 2.1 m. Therefore, the velocity is found to be 7.03 m/s, and it is within the acceptable range.

To be sure about the design characteristic's it is worth to compare it with actual installed PHES around world. Table 4.2 shows the technical specifications of reference pumped storage stations and current PHES design.

Table 4.2: Installed PHES stations in the world and current PHES (Tianhuangping Pumped-Storage Hydro Plant - Power Technology. 2005)

PHES Station	**Rated Capacity (MW)**	**Units Number**	**Elevation Difference (m)**	**Q/Unit (Pumping) (m^3/s)**	**Q/Unit (Generating) (m^3/s)**	**Conduit Diameter (m)**	**Flow Speed (Pumping) (m/s)**	**Flow Speed (Generating) (m/s)**
Tianhuangping (China, 2001)	1836	6×306 MW	590	47.6	58.8	3.2	5.9	7.3
Ludington (USA, 1973)	1872	6×312 MW	111	258	318	7.3	6.1	7.6
Current PHES	150	2×75 MW	349	20.1	24.3	2.1	5.8	7.03

4.8.2 Dynamic head calculation (Head loss)

The dynamic head is generated as a result of friction within the system. The dynamic head is calculated using the basic Darcy Weisbach equation (Milnes, 2000) given by:

$$H_d = \frac{K \times v^2}{2 \times g} \tag{4.7}$$

Where:

H_d = Dynamic head.

K = Loss coefficient.

v = Velocity in the pipe (m/s).

g = Acceleration due to gravity (m/s^2).

The loss coefficient K is made up of two elements:

$$K = K_{Pipe} + K_{Fitting} \tag{4.8}$$

$K_{Fitting}$ is associated with the fittings that are used in the pipework's of the system to elevate the water from lower reservoir to upper reservoir. Their Values can be obtained from standard tables and a total $K_{Fitting}$ value that can be calculated by adding all the $K_{Fitting}$ values for each individual fitting within the system. The following table shows the calculation of K fittings that have been used in this work. From the Table 4.3 the total $K_{Fitting}$ value has been calculated and it equals to 7.48.

Table 4.3: Calculation of K fittings ("Friction Losses in Pipe Fittings," n.d.)

Fitting Items	**Quantity**	$\boldsymbol{K_{Fitting}}$ **Value**	**Item total**
Pipe entry projecting	1	0.78	0.78
Pipe exit to container	1	1	1
Elbow 45°	30	0.19	5.7
Total $\boldsymbol{K_{Fitting}}$ **value**			7.48

K_{Pipe} is associated with the straight lengths of pipe used within the system and is defined as:

$$K_{Pipe} = \frac{f \times L}{D} \quad (4.9$$

Where:

f = Friction coefficient.

L = Pipe length (m).

D = Pipe diameter (m).

The friction coefficient f can be found using a modified version of the Colebrook White equation:

$$f = \frac{0.25}{\left[\log\left\{\frac{\varepsilon}{3.7 \times D} + \frac{5.74}{Re^{0.9}}\right\}\right]^2} \quad (4.10)$$

Where:

ε = Roughness factor (m)

Re = Reynold number

The pipe roughness factor ε is a standard value that is obtained from standard tables. Reynolds number is a dimensionless quantity associated with the smoothness of flow of a fluid and relating to the energy absorbed within the fluid as it moves (Milnes, 2000). For any flow in pipe, Reynolds number can be calculated using the following formula:

$$Re = \frac{\nu \times D}{\upsilon} \tag{4.11}$$

Where:

υ = Kinematic viscosity (m^2/s).

4.8.3 Total head calculation

Total pump head can be calculated by using equation (4.12) as follows:

$$P_H = H_s + H_d + \left(L_{Upper.r} - L_{Lower.r}\right) \tag{4.12}$$

Where:

H_s = Static head (height difference between upper and lower reservoirs).

H_d = Dynamic head (losses).

$L_{Upper.r}$ = Water height in upper reservoir.

$L_{Lower.r}$ = Water height in lower reservoir.

It is worth to mention that the total pump head is varying when the values of $L_{Upper.r}$ and $L_{Lower.r}$.are changed.

4.8.3.1 Sample of calculation

From Table (4.2) Total $K_{Fitting}$ value is 7.48

Find Reynold number at rated capacity. Where the kinematic varicosity of water υ =1.0 $* 10^{-6}\, m^2/s$

$$Re = \frac{v \times D}{\upsilon}$$

$$= \frac{5.8\, m/s * 2.1m}{1.1 * 10^{-6}\, m^2/s}$$

$$= 121.8 \times 10^5\ turbelnt$$

Now substitute the value of Reynold number in equation (4.10):

$$f = \frac{0.25}{[\log\{\frac{\varepsilon}{3.7 \times D} + \frac{5.74}{Re^{0.9}}\}]^2}$$

$$= \frac{0.25}{[\log\{\frac{4.6 \times 10^{-6}}{3.7 \times 2.1} + \frac{5.74}{(121.8 \times 10^5)^{0.9}}\}]^2}$$

$$= 0.00969$$

K_{Pipe} can be calculated by substituting the value of (f) in equation (4.9):

$$K_{Pipe} = \frac{f \times L}{D}$$

$$= \frac{0.00969 \times 1500m}{2.1m}$$

$$= 6.92$$

Then, using equation (4.8), the total K value for the system is:

$$K = K_{Pipe} + K_{Fitting}$$

$$= 6.92 + 7.48$$

$$= 14.4$$

Now the dynamic head can be calculated by using equation (4.7) as follows:

$$H_d = \frac{K \times v^2}{2 \times g}$$

$$= \frac{14.4 \times 5.8^2}{2 \times 9.8}$$

$$= 24.7\ m.hd$$

Finally, the total pump head is calculated by using equation (4.12):

1-first scenario: when the $L_{Upper.r}$ is minimum.

$$P_H = H_s + H_d + \left(L_{Upper.r} - L_{Lower.r}\right)$$

$$= 335\ m + 24.7\ m + (0\ m - 4\ m)$$

$$= 355.7\ m$$

2- second scenario: when the $L_{Upper.r}$ is maximum.

$$P_H = H_s + H_d + \left(L_{Upper.r} - L_{Lower.r}\right)$$

$$= 335\ m + 24.7\ m + (14\ m - 4\ m)$$

$$= 369.7\ m$$

3- third scenario: when the $L_{Upper.r}$ is between the minimum and maximum level.

$$P_H = H_s + H_d + \left(L_{Upper.r} - L_{Lower.r}\right)$$

$$= 335\ m + 24.7\ m + (7\ m - 4\ m)$$

$$= 362.7\ m$$

Chapter Five

Power System Modeling

5.1 Power system characteristics

As known any power generation system may consist of various generating units including: thermal generating units, wind farms, solar stations. While the operation these units depend on many characteristics. The operation of thermal units depends on fuel price ($/MMBTU), start cost ($), shutdown cost ($), heat consumption rate (MMBTU /MWh), operation and maintenance cost. The operation of wind farms only depends on the availability of the wind.

Likewise, there are a many constrains that controlling the operation of generating units within the power system as following:

1- Max unit capacity
2- Minimum stable level
3- Max ramp rate Up/Down
4- Minimum time Up/Down

For PHES, there is additional constrains for pump/turbine unit:

1- Pump load
2- Minimum pump load
3- Pump efficiency
4- Upper/Lower reservoirs capacity

This research aims to simulate the operation of the practical power system in two scenarios when wind farms are hocked up without PHES and with inclusion of PHES. Since the power system includes various type of thermal generating units, wind farms and PHES with many constrains. Therefore, this problem can be dealt with by the Mixed Integer Programming (MIP) problems.

5.2 MIP problem

The most common method to solve MIP problem is the Branch and Bound (B&B) algorithm method. The branch-and-bound method works by finding better integer solutions and also bounding the linear relaxation as it moves through the tree of integer combinations. Thus, at the optimal solution the relative gap is zero, even though the linear relaxation and integer optimal solutions to the original problem might have quite different objective function values.

There are two central ideas in the B&B method (Hillier,1986).

1- Branch: It uses the linear programming relaxation to decide how to branch. Each branch will add a constraint to the previous linear programming relaxation in order to enforce an integer value on one variable that was not an integer in the predecessor solution.

2- Bound: It maintains the best integer feasible solution obtained so far, as a bound on tree-paths that should still be searched.

If any tree node has an objective value less optimal than the identified bound, no further searching from that node is necessary, since adding constraints can never improve an objective. If any tree node has an objective value more optimal than the identified bound, then additional searching from that node is necessary.

5.2.1 PLEXOS Software

An academic version of PLEXOS for Power Systems, is used in this research which is a simulation software for energy market analysis. PLEXOS is tried-and-true simulation software that uses state-of-the-art mathematical optimisation combined with the latest data handling and visualisation and distributed computing methods, to provide a high-performance, robust simulation system for electric power, water and gas that is leading edge yet open and transparent. PLEXOS meets the demands of energy market participants, system planners, investors, regulators, consultants and analysts alike with a comprehensive range of features seamlessly integrating electric, water, gas and heat production, transportation and demand over simulated timeframes from minutes to 10's of years, all delivered through a common simulation engine with easy-to-use interface and integrated data platform. PLEXOS is one of the fastest and most sophisticated software available today ("Energy Exemplar," 2017.).

PLEXOS for Power Systems is integrated with fastest mathematical programming solvers such as MOSEK, Xpress-MP, CPLEX and GUROBI. In this research MOSEK solver is used since it is included in the academic package license of the PLEXOS software and has the ability to solve MIP problem.

5.3 Practical system data

All the power model data is obtained from NEPCO

5.3.1 Defining the conventional units

The simulated power system will consist of all conventional generating units in Jordan. The details of the conventional generating units of the practical power system are given in Table 5.1. Thermal generators are modeled by defining their maximum/minimum capacity, ramp rates, start cost, its initial status (ON or OFF), and number of hours the unit has been ON or OFF. The characteristics of thermal generators are obtained from NEPCO. The fuel cost of all thermal units was based on the fuel cost forecast of year 2017.

Table 5.1: Generating units of practical system

Plant name	**Unit #**	**Type of unit**	**Available capacity (MW)**	**Minimum capacity (MW)**
Samra (1)	2	Combined Cycle	150	115
Samra (2)	2	Combined Cycle	150	115
Samra (3)	2	Combined Cycle	210	120
Samra (4)	1	Gas Turbine	146	50
Amman East	2	Combined Cycle	185	120
Amman South	1	Gas Turbine	30	20
Qatrana	2	Combined Cycle	190	120
IPP3	38	Diesel Engine	15	0
IPP4	16	Diesel Engine	15	0
Risha(1)	3	Gas Turbine	30	20
Risha (2)	2	Gas Turbine	30	20
Rehab (1)	2	Gas Turbine	30	20
Rehab (2)	2	Combined Cycle	135	90
Hussein	3	Steam	60	25
Aqaba Tharmal Station (1)	2	Steam	120	55
Aqaba Tharmal Station (2)	3	Steam	120	55

5.3.2 Defining wind farms

The power system in this work will simulate the scenario of adding 1200 MW of wind power to the electrical grid in 2020 with and without PHES. The actual hourly wind speed data which is collected from Tafila wind farm will be used as a reference percentage for the rating factor. Figure 5.1 shows the hourly data for Tafila wind farm with 117 MW total capacity.

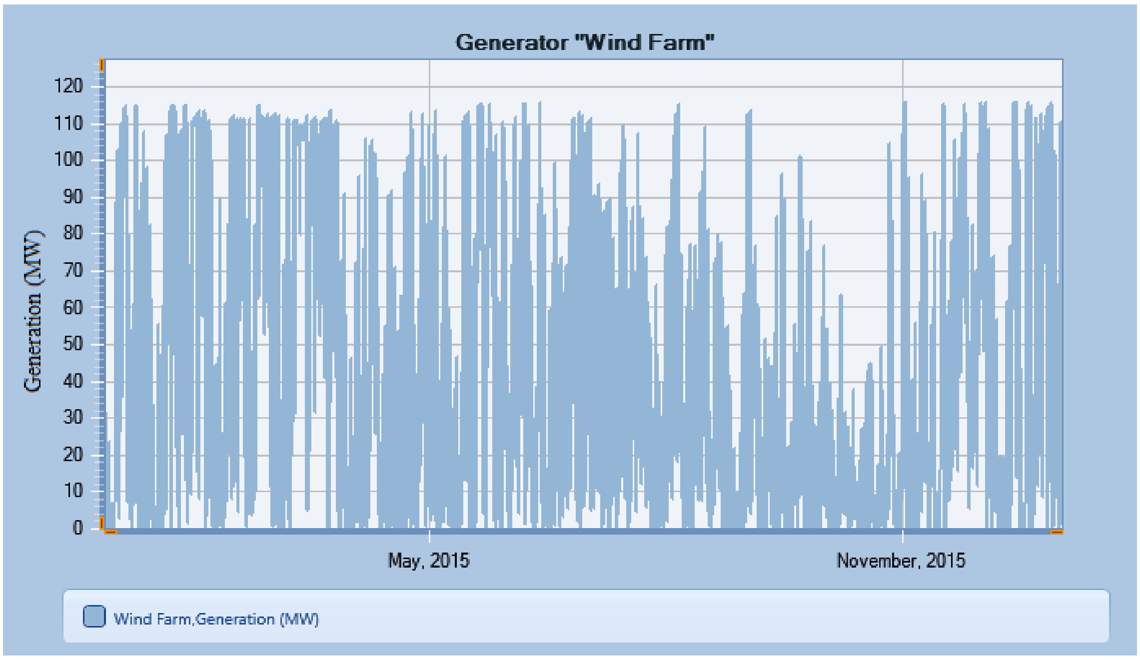

Figure 5.1: Hourly power data for Tafila wind farm

5.3.3 Defining PHES

Different PHES capacities will be compared economically in this research. PLEXOS software recognizes the Gen/Pump machine through specific characteristics as shown in Table 5.2. Also, as shown in Table 5.3 and as shown in Table 5.4, it recognizes the upper and lower storage by max capacity (GWh), initial capacity (GWh) and minimum capacity (GWh).

Table 5.2: Entry data for PHES units

Unit No.	Max Capacity (MW)	Min Stable Level (MW)	Pump Load (MW)	Min Pump Load (MW)	Max Ramp Up (MW/min)	Max Ramp Down (MW/min)	Pump Efficiency %	O&M Cost $/MWh
2	75	20	75	20	75	75	81	5
4	75	20	75	20	75	75	81	5

Table 5.3: Entry data for reservoirs capacity of 150 MW PHES

	Max Capacity (GWh)	Initial Capacity (GWh)	Min Capacity (GWh)
Upper Reservoir	1.5	0.5	0.19
Lower Reservoir	16.8	5	2

Table 5.4: Entry data for reservoirs capacity of 300 MW PHES

	Max Capacity (GWh)	Initial Capacity (GWh)	Min Capacity (GWh)
Upper Reservoir	5	0.5	0.19
Lower Reservoir	16.8	5	2

5.3.4 Defining load data

Actual hourly load data for Jordan in 2015 is used for practical system, it has a peak of 3250 MW as shown in Figure 5.2. A sample of data can be found in appendix B.

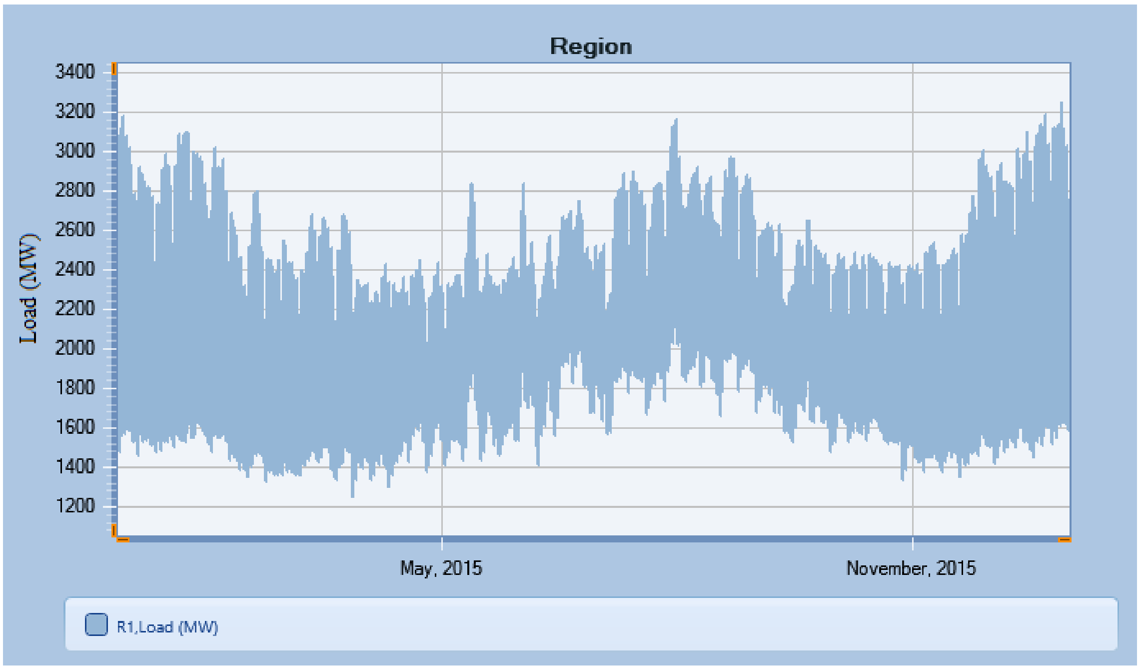

Figure 5.2: Hourly Load data for Practical system

5.3.5 Transmission Line Losses

All the generators and the loads are considered connected to the same node which means that the transmission system losses and line congestions are ignored in the simulation of the practical system model.

5.4 Test system data

The modeling of a simple test system consisting of only 16 units is conducted for the purpose of giving an idea how the software solves the given optimization problem. The test system modeled for this purpose consists of, base generator 1&2, diesel generator, Lower efficiency generator (HFO), wind farm and a PHES unit. The details of the test system are given in Table 5.5 below.

Table 5.5: Generating units for the test model

	Units	Base Gen 1	Base Gen 2	Diesel Gen	HFO Gen	Wind Farm	PHES
No of Units	No.	2	1	8	1	1	3
Max Capacity	MW	110	80	15	120	117	23.4
Min Stable Level	MW	80	30	0	30	-	10
Heat Rate	MMBTU/MWh	7	7.10	8.6	10	-	-
Max Ramp Up	MW/min	7	7	5.5	11	-	23.4
Max Ramp Down	MW/min	7	7	5.5	11	-	23.4
Min Up Time	Hrs	6	6	1	6	-	0
Min Down Time	Hrs	6	6	1	6	-	0
Start Up Cost	$	7300	7500	0	5200	-	-
O&M Cost	$/MWh	0.12	0.1	12	0.13	-	5
Pump Load	MW	-	-	-	-	-	23.4
Min Pump Load	MW	-	-	-	-	-	10
Pump Efficiency	%	-	-	-	-	-	81

5.4.1 Defining wind farm

Figure 5.3 shows an actual wind power data for one year that has been collected from Tafila wind station which has a rated capacity of 117 MW. Power data will be used in the test system to evaluate the negative impact on the power grid during off peak period. A sample of data can be found in appendix B.

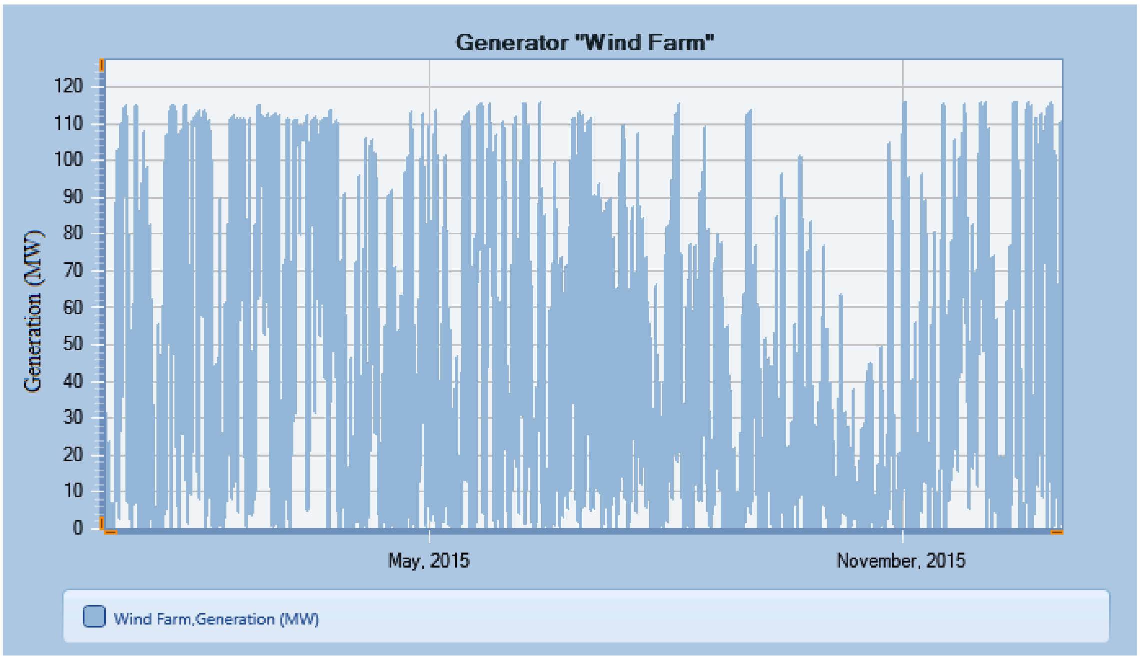

Figure 5.3: Hourly power data for the wind unit

5.4.2 Defining PHES unit

Three units of reversible pump-turbine with a rated capacity of 23.4 MW will be used in the test system. The round-trip efficiency of 81 % is used which is within the globally accepted efficiency range of 75% to 85 %. The upper reservoir has a maximum storage capacity of 0.8 GWh and its minimum permissible storage is 0.15 GWh. Table 5.6 shows the characteristics of PHES unit.

Table 5.6: PHES entry data for test model

Units No.	Max Capacity (MW)	Min Stable Level (MW)	Pump Load (MW)	Min Pump Load (MW)	Max Ramp Up (MW/min)	Max Ramp Down (MW/min)	Pump Efficiency %	O&M Cost $/MWh
3	23.4	10	23.4	10	23.4	23.4	81	5

5.4.3 Defining load data

As shown in figure 5.4 real hourly load data of the south region in 2015 is used in the test system. It has a peak of 350 MW and a base of 150 MW.

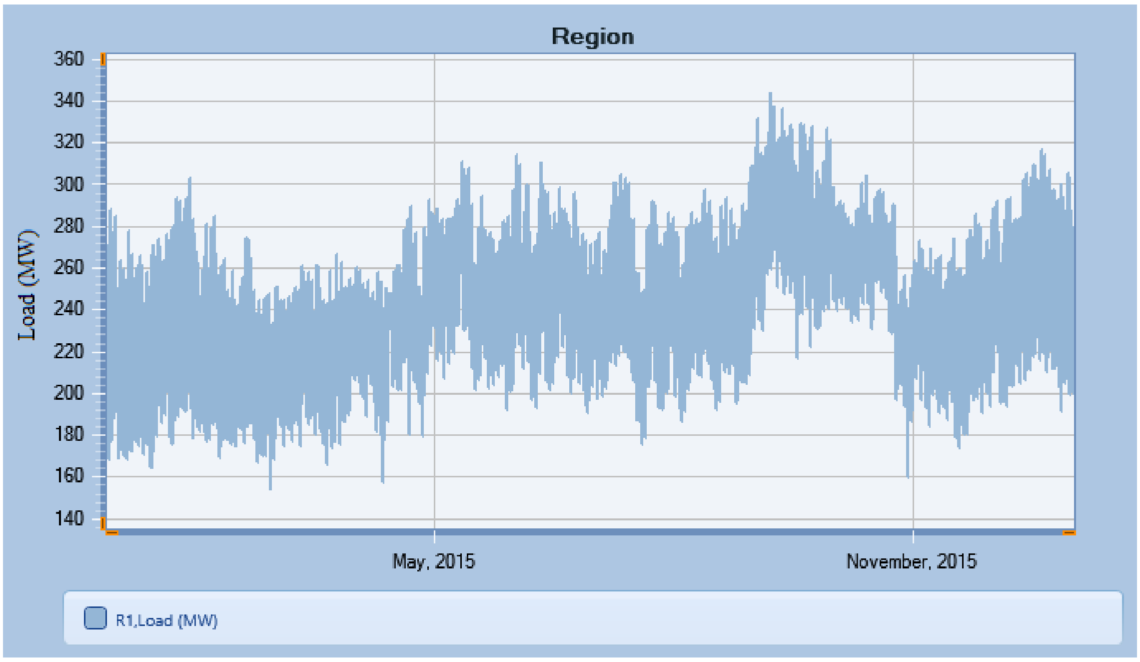

Figure 5.4: Hourly load data for test model

Chapter Six

Results and discussions

6.1 Test system model results

In the test system three cases have been simulated which are: 1- Conventional generation without wind farm (Gas only), 2-Conventional generation with wind farm (Gas+Wind), 3-Conventional with wind farm and PHES is included (Gas+Wind+HPES). The simulation was run over a time horizon of one year with an interval of one hour.

PLEXOS software can recognize the wind power data through two methods which are: inputting a max capacity MW and rating power MW, inputting max capacity MW and rating factor 100%. Through these methods, the wind power can be curtailed when there is more power and the demand side is low. If it is necessary to make wind power data constant as inputted, it is possible by using fixed load property. Therefore, a dump energy can be easily observed through the period that has rich wind power along with low demand (off peak).

This test system model aims to clarify how PLEXOS solves a given optimization problem and also to show where the dump energy starts to appear. Therefore, the hourly wind power data which has a maximum capacity of 117 MW has been used through two methods fixed load and rating power.

6.1.1 First case: conventional without wind & PHES (Gas only)

In this scenario, only conventional generators are operated to fulfil the demand side. It is the normal situation without wind farm or any storage. As shown in Figure 6.1 and Figure 6.2 the generation curve dramatically matches the load curve. This indicates that the dump energy is zero since all generators follow the demand load smoothly without any sudden change. Table 6.1 gives the region data including summation of load, generation and dump energy over the simulated year.

Table 6.1: First case results (Gas only)

Property	**Units**	**R1**
Load	MWh	2134415.30
Generation	MWh	2134415.30
Dump Energy	MWh	0

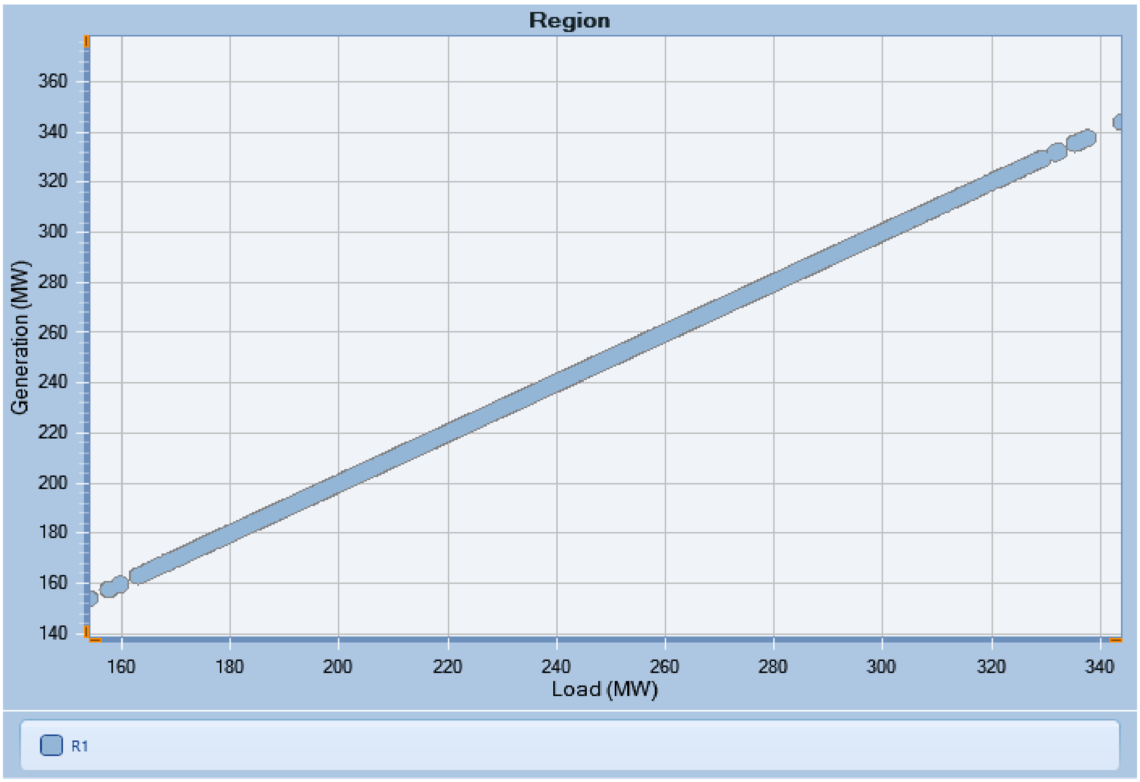

Figure 6.1: Results for Load and Generation

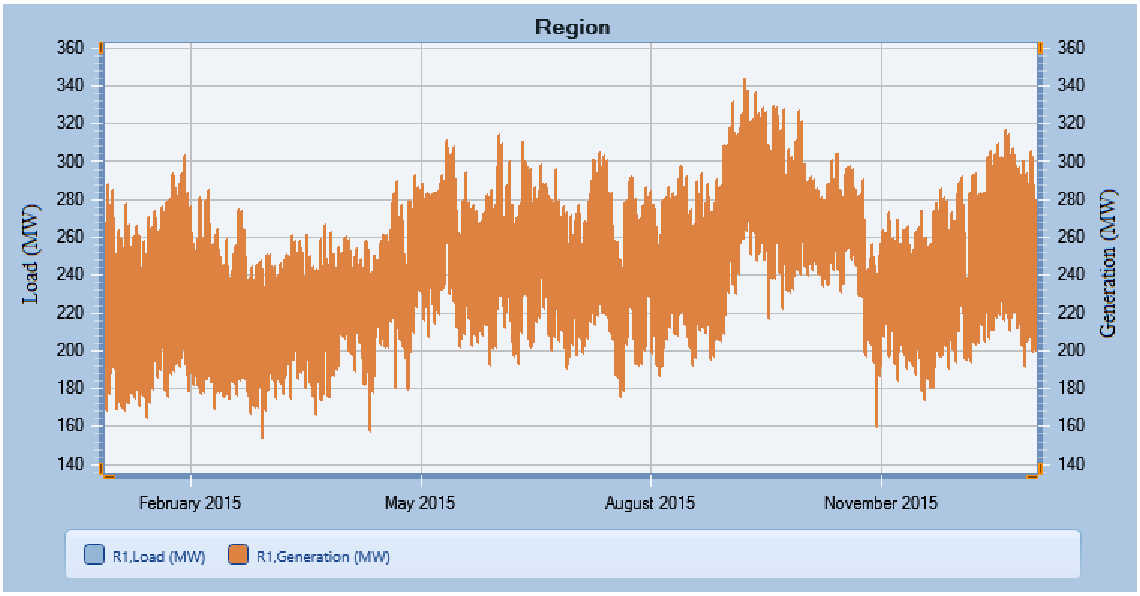

Figure 6.2: Generation and load through one year horizon for the first case

6.1.2 Second case: conventional and wind without PHES (Gas+Wind)

The second case has the same characteristics of the first case but now, Tafila wind farm has been hocked up to the power system by using real hourly data for one year. This scheme is still running without any storage system.

In the first scenario as indicated in Figure 6.3 after using the wind data as a fixed load, the generation and load curves don't match each other so there is a dump energy appears in certain periods of the low demand load through the simulation time horizon of one year as shown in Figure 6.4.

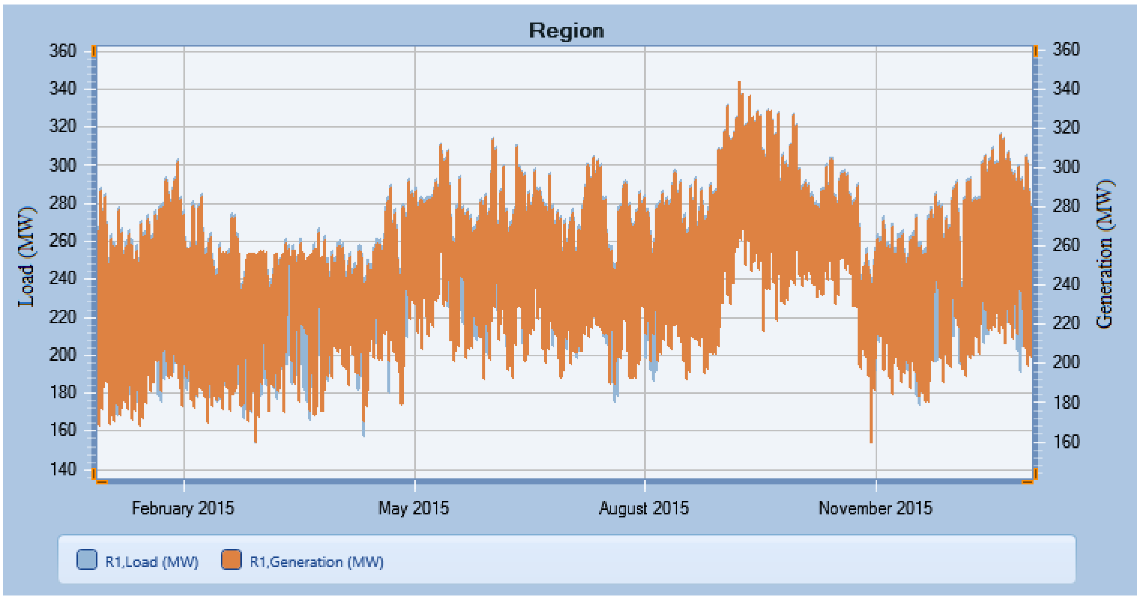

Figure 6.3: Generation and load through one year horizon for the second case

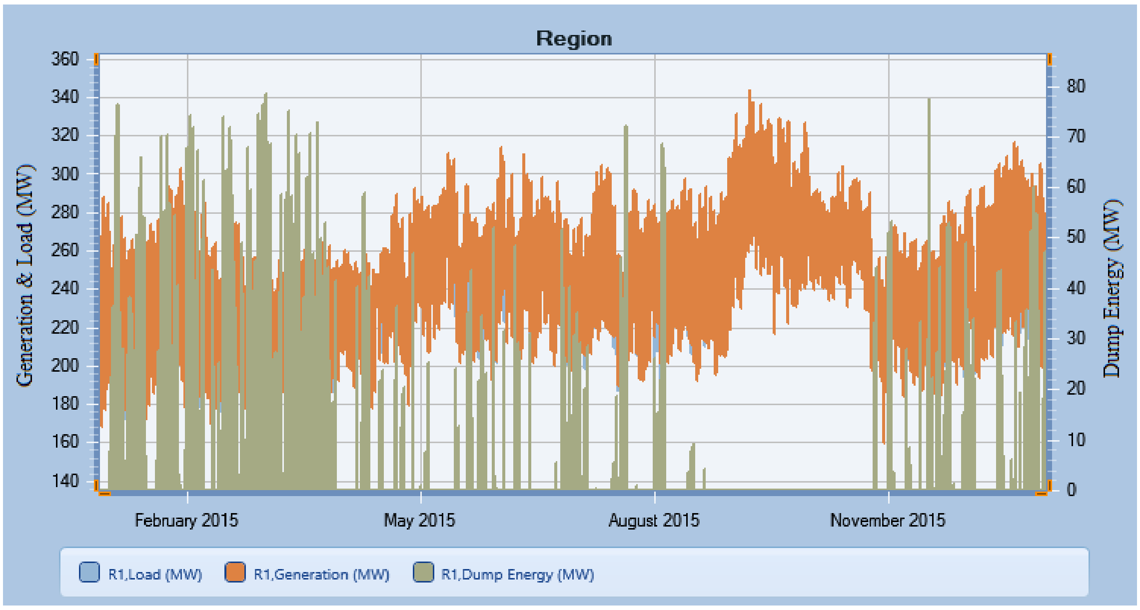

Figure 6.4: Dump energy within low demand period

Now by executing the solution over one weak period the dump energy can be observed clearly. Figure 6.5 shows the relation between the demand (load) and the dump energy.

It is obvious that the off-peak periods have the major of dump energy. And that gives an indication about the mess matching between the demand load and wind generation load.

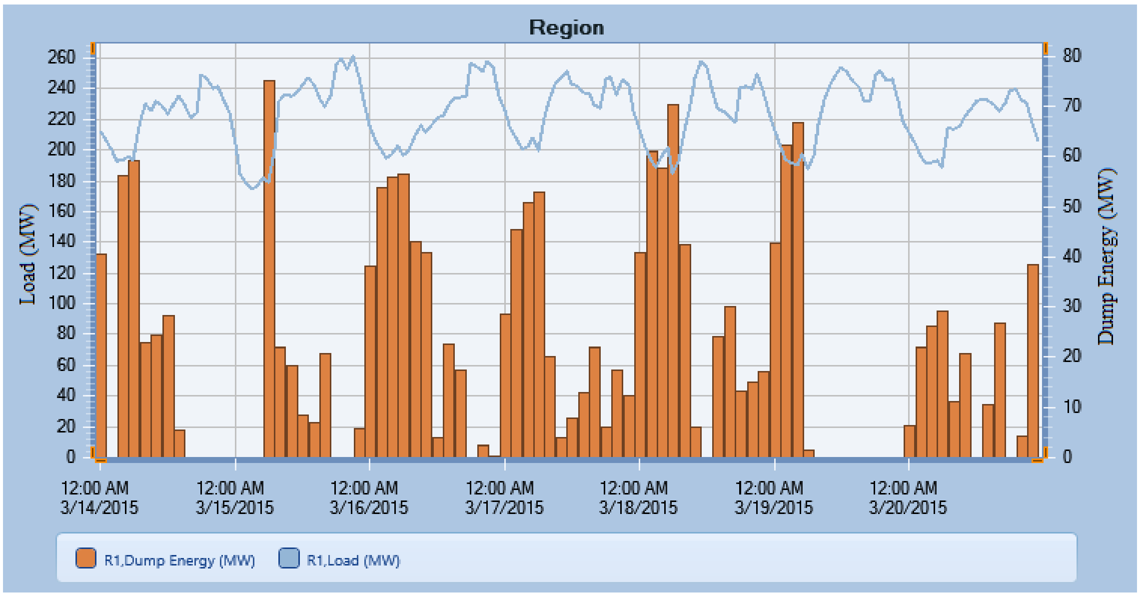

Figure 6.5: Dump energy with the demand load over one week

In the second scenario, the wind data was used as in the essential methods that mentioned before (i.e. max capacity MW and rating power MW, max capacity MW and rating factor 100%). The summation of wind power data was 369.7 GWh but after executing the model it is curtailed to be 353.4 GWh. The curtailed energy approximately equals to dump energy in the first scenario after using the wind data as fixed load.

6.1.3 Third case: conventional and wind with PHES (Gas+Wind+PHES)

Third case has the same characteristics in the first and second cases but now with inclusion of PHES unit. Conventional generators as it may be known have two limits of operation capacity which are the maximum available capacity and the minimum stable level. Within low demand period, only base load generators will be operated with capacity near the minimum stable level of operation. In case the wind farms are connected to the power system and there is high potential wind power within the low demand period (off-peak), this can adversely affect the operation of base load generators since they can't operate below the minimum stable level. Therefore, wind generator units may curtail to avoid the problems resulting from excess energy in the electrical grid as explained in the previous section. When PHES is hocked up to the power system, it can absorb all the energy that is generated during off peak periods from the uncertain sources such as wind farms.

6.1.3.1 PHES operation with a price

PLEXOS software optimizes the operation of PHES unit by depending on the energy price. This can be done by pumping water into the upper reservoir within the low-price period and releasing it through the high price period. Figure 6.6 shows the operation of PHES with respect to the energy price for one week.

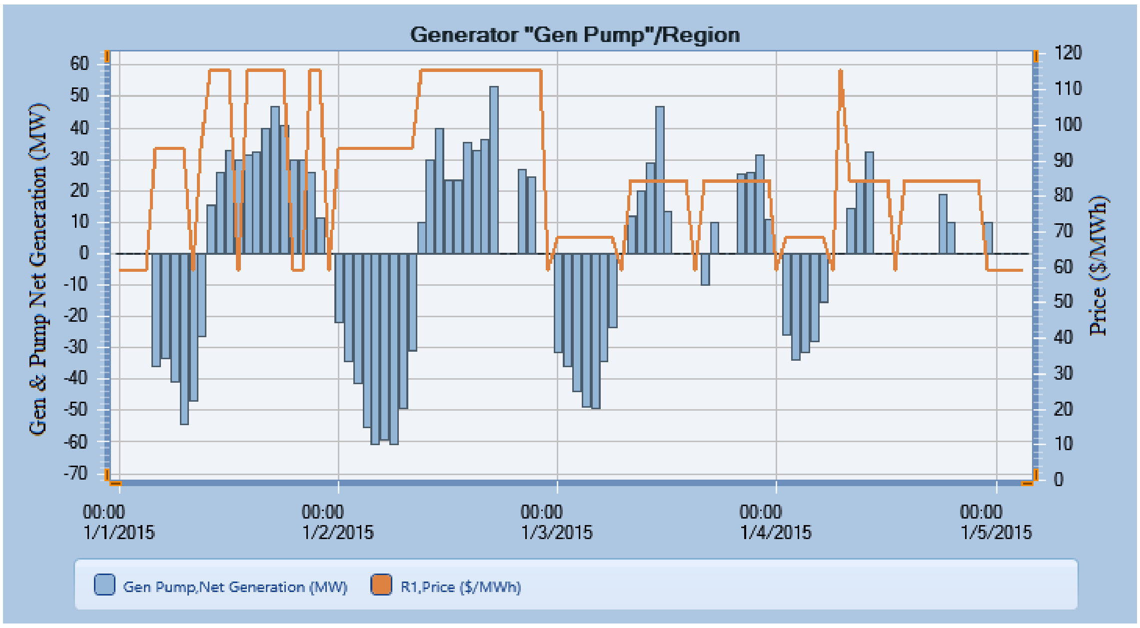

Figure 6.6: PHES operation with price

6.1.3.2 PHES operation method

Inclusion of the PHES unit into the power system along with wind farms can reduce the generation from expensive diesel or oil units and inefficient units, while increasing the generation from cheap natural gas units and increasing wind integration level.

In the first scenario (without PHES), the operation of conventional generators is highly dependent on wind generation. Since wind is uncertain power source, this will affect the ramp rate of base and peak generators. In the second scenario when PHES starts to operate along with the power system, a significant change on the behavior of the whole system can be observed. PHES increases the generation from the high efficiency generators at off peak periods and reduces the generation from inefficient generator by peak shaving at high demand period. Table 6.2 shows comparison of system operation between the two scenarios. Table 6.3 provides the total pump load and generation for PHES unit over the simulated year.

Table 6.2: Summation of generation over one year for two scenarios

Generator	Generation (GWh)	
	without PHES	with PHES
Base Gen 1	1584.36	1613.79
Base Gen 2	167.77	146.07
HFO Gen	17.98	11.75
Diesel GEN	10.79	1.36
Wind Farm	353.47	369.71

Table 6.3: Total Pump load, Generation and net generation for PHES unit

Pump Load (GWh)	44.9
Generation (GWh)	36.5
Net generation (GWh)	-8.4

6.2 Practical system results

The simulation for the practical power system is executed for two scenarios. The first scenario is including thermal generating units and wind farms without PHES. The second scenario is including thermal generating units and wind farms with PHES. The second scenario has been run through two different rated capacities of PHES (150 & 300) MW to compare the increased in wind power integration for each capacity and make the decision as shown in Table 6.4.

For all the scenarios, the model was configured to undertake one year of optimization that is starting from January 2015 to December 2015 with hourly intervals of (8760 hour) and one week look-ahead period of one hour resolution. The simulation is proceeded by solving these steps in chronological sequence. The model was solved by using the MOSEK solver with a relative gap of 0.1 % and the maximum time for search of 250 seconds. The executed time for each scenario was about one hour. Notably, this model is solved with the optimal unit commitment method. Therefore, the excess energy generated by the wind farm is going to be minimal despite the actual scenario.

As shown in Table 6.4 the model has been run with two different capacities of PHES unit. One of 150 MW and the other of 300 MW. The 150 MW capacity of PHES unit is found to be the optimal size for the 1200 MW of wind integration level. The increase in energy recovery does not exceed 8.9 GWh for the case of 300 MW (i.e. in the case of 150 MW the energy recovery is 31.29 GWh while in the case of 300 MW the recovery is 40.1 GWh.

Table 6.4: Increasing of wind integration level

Scenario	**Wind Integration Level (GWh)**	**Increasing (GWh)**
Without PHES	3742.199	-
PHES 150 MW	3773.497	31.298
PHES 300 MW	3782.493	40.1

6.2.1 Mismatch between the demand and the wind generation

The hourly average for the demand load and the wind generation in Jordan have been analyzed. Figure 6.7 shows that the off-peak period is extend from 1 AM to 6 AM and Figure 6.8 indicates that the average wind generation has maximum level within this period. This will lead to cause problem of balancing between generation and demand load within this period unless the PHES system is utilized. That is the key role of using such system to store the excess energy within low demand period.

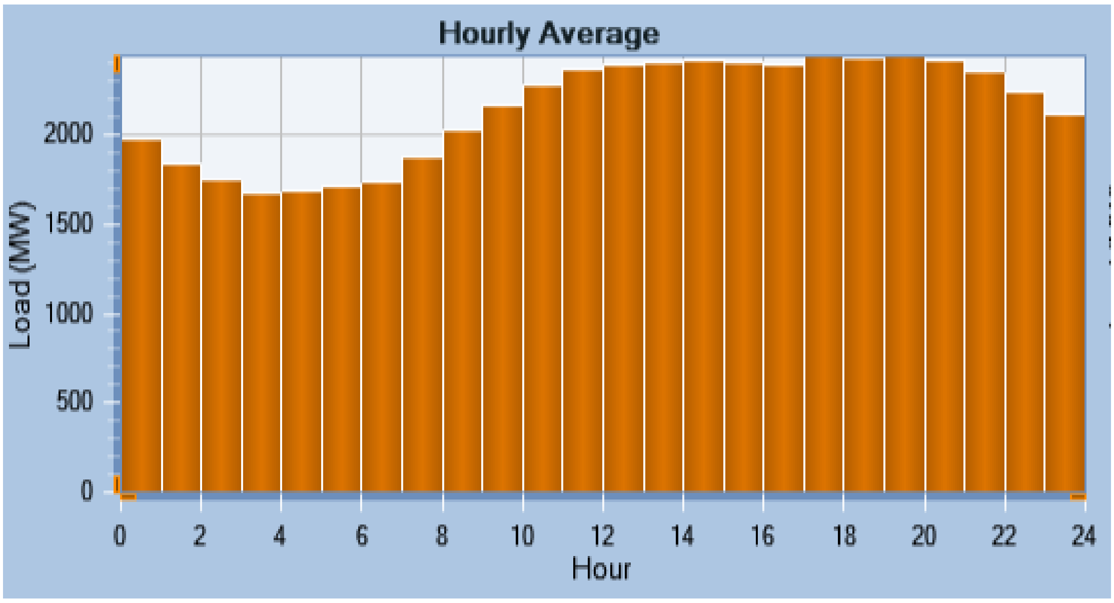

Figure 6.7: Load hourly average

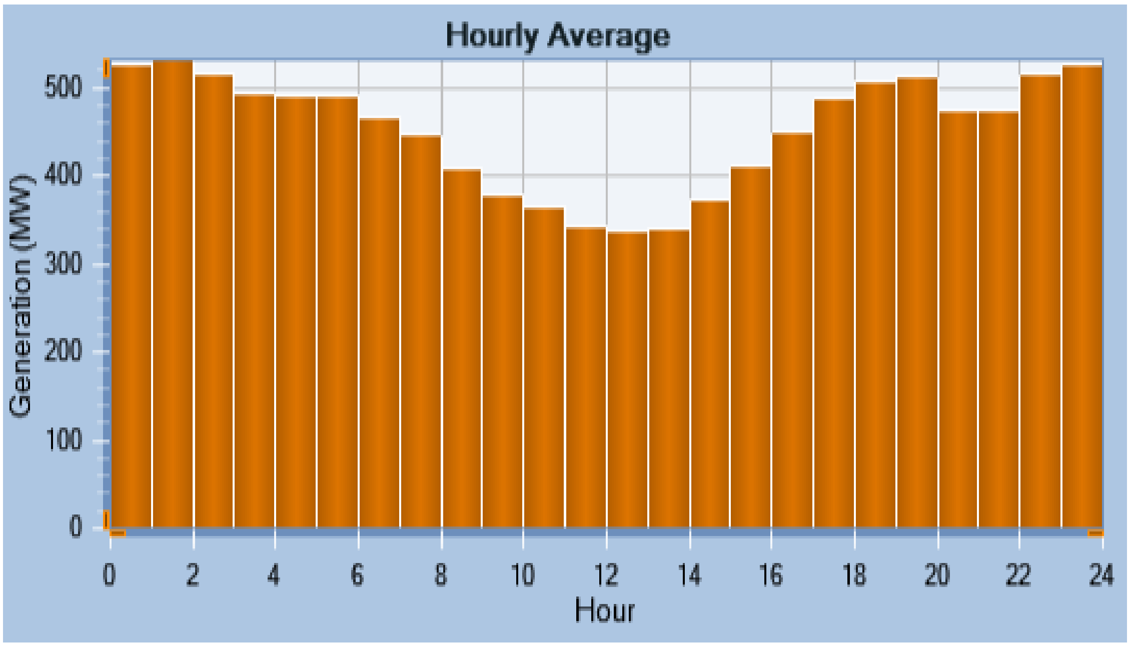

Figure 6.8: Wind generation hourly average

Figure 6.9 shows the behavior of the PHES operation in the practical system with the generated power from the wind farms.

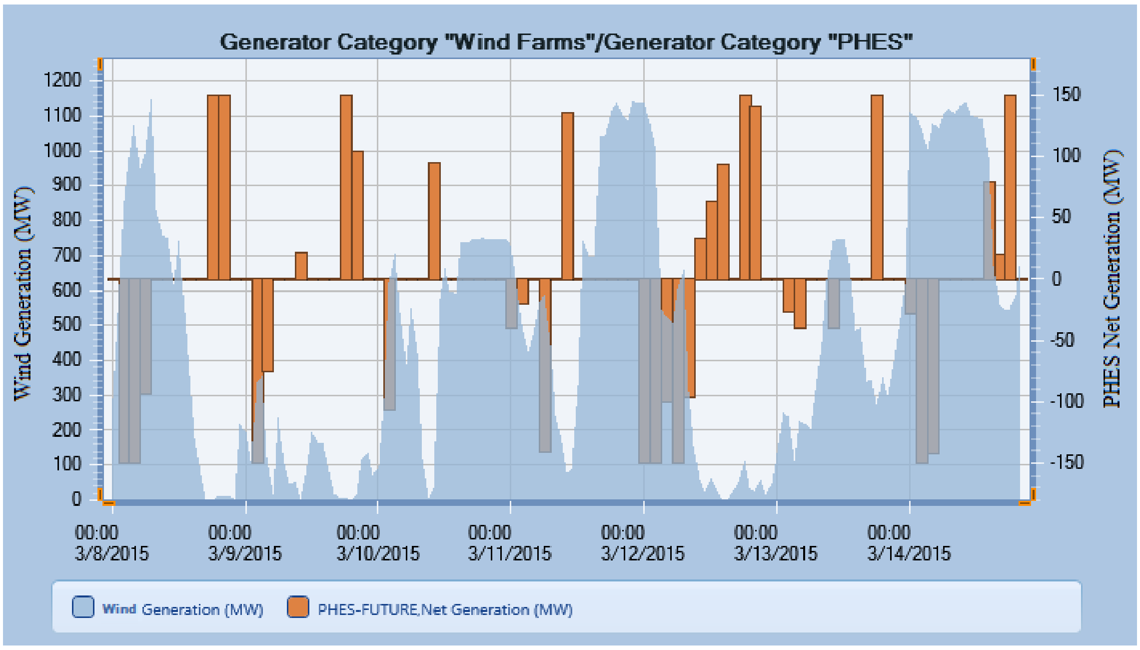

Figure 6.9: PHES operation with wind Farms in the practical system

6.2.2 Operation method of PHES in the practical model

PLEXOS software optimizes the operation of PHES unit by depending on the energy price and the excess of energy. This can be done by pumping water into the upper reservoir within the low-price period and releasing it through the high price period. Figure 6.10 shows the operation of PHES with respect to the energy price.

Figure 6.11 also indicates the period of pumping mode and generating mode with respect to the load demand. The PHES will operate as a pump only in the low demand load period while operating as a generator in the high demand load period.

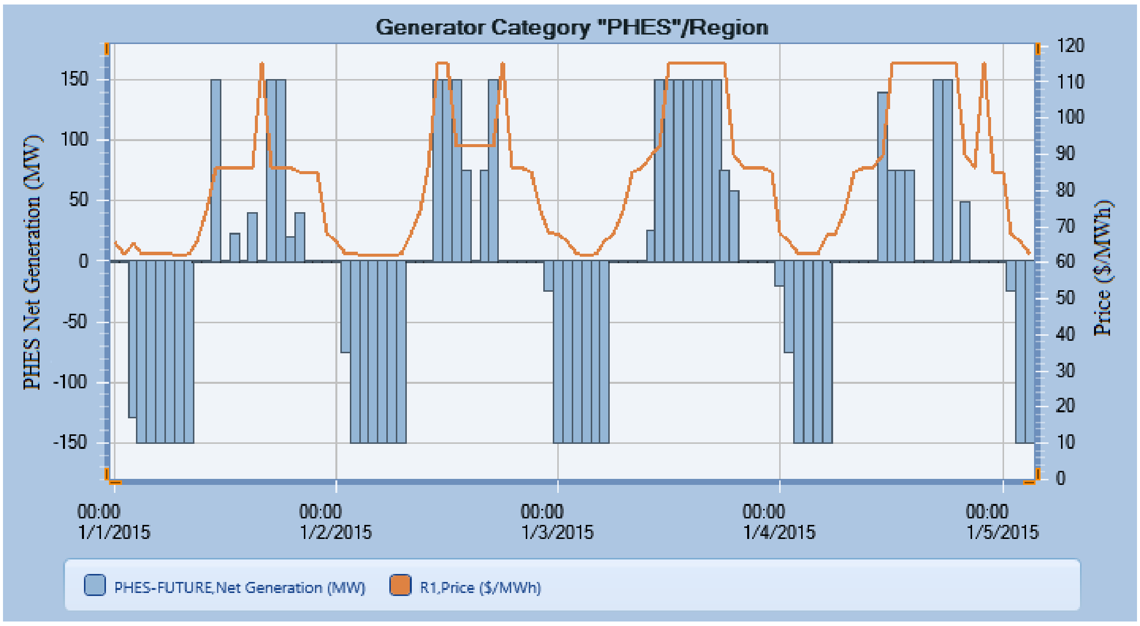

Figure 6.10: PHES operation with price in practical system

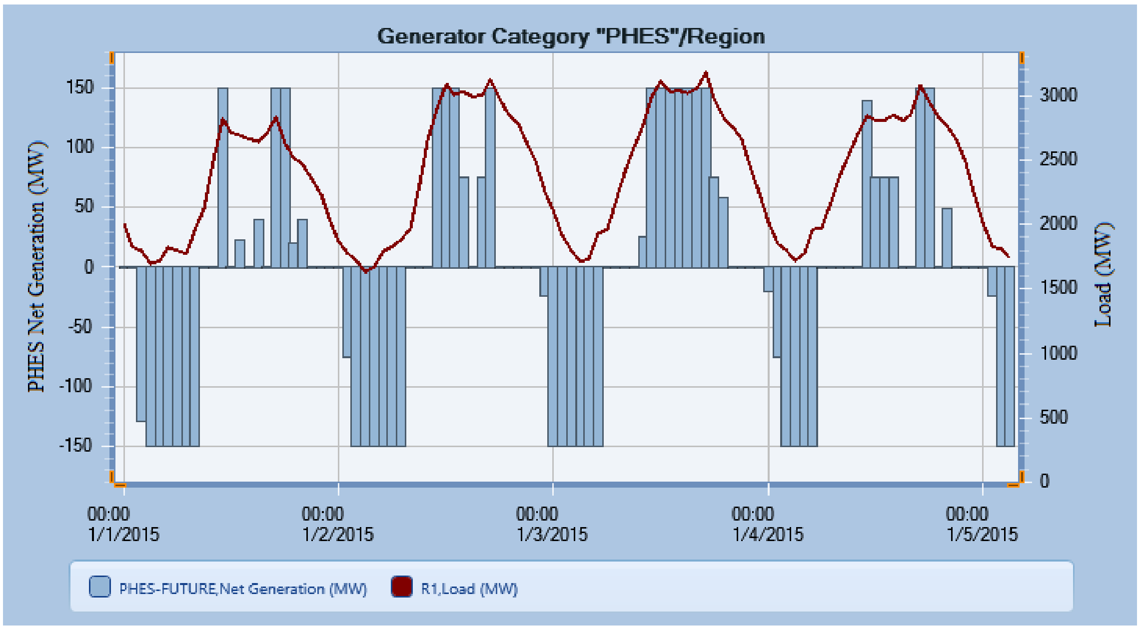

Figure 6.11: PHES operation with demand load in practical system

Figure 6.12 shows the changing in the storage capacity (GWh) of the upper reservoir (Head) and the lower reservoir (Tail) while the system operating. The upper reservoir as mentioned before is operating between the maximum storage capacity 1.5 GWh and minimum storage capacity of 0.19 GWh.

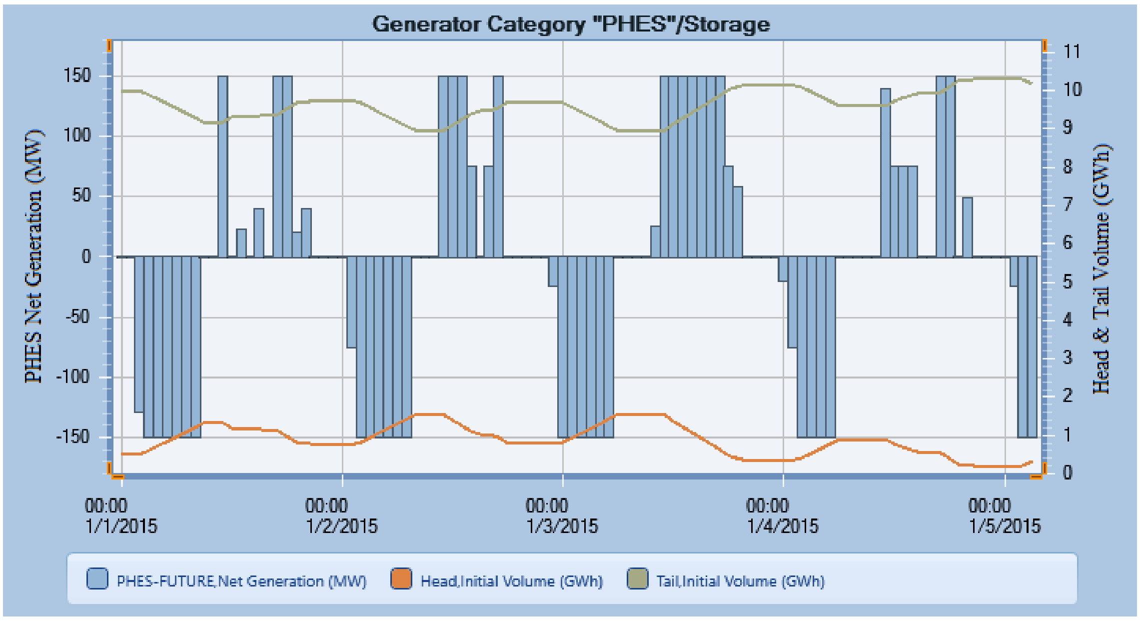

Figure 6.12: Changing in the capacity of the Upper/Lower reservoirs

6.2.3 Dispatch results

As indicated early in the test system, inclusion of the PHES unit into the power system along with wind farms reduces generation from expensive diesel and oil units or inefficient units, while increasing generation from the cheap natural gas units and increasing wind integration level. Figure 6.13 shows a comparison between the value of generated power that is supplied to the grid from IPP4 station which contains diesel generators for the two scenarios with and without PHES. As shown in Figure 6.13 the generation from diesel units has been reduced when the PHES is included.

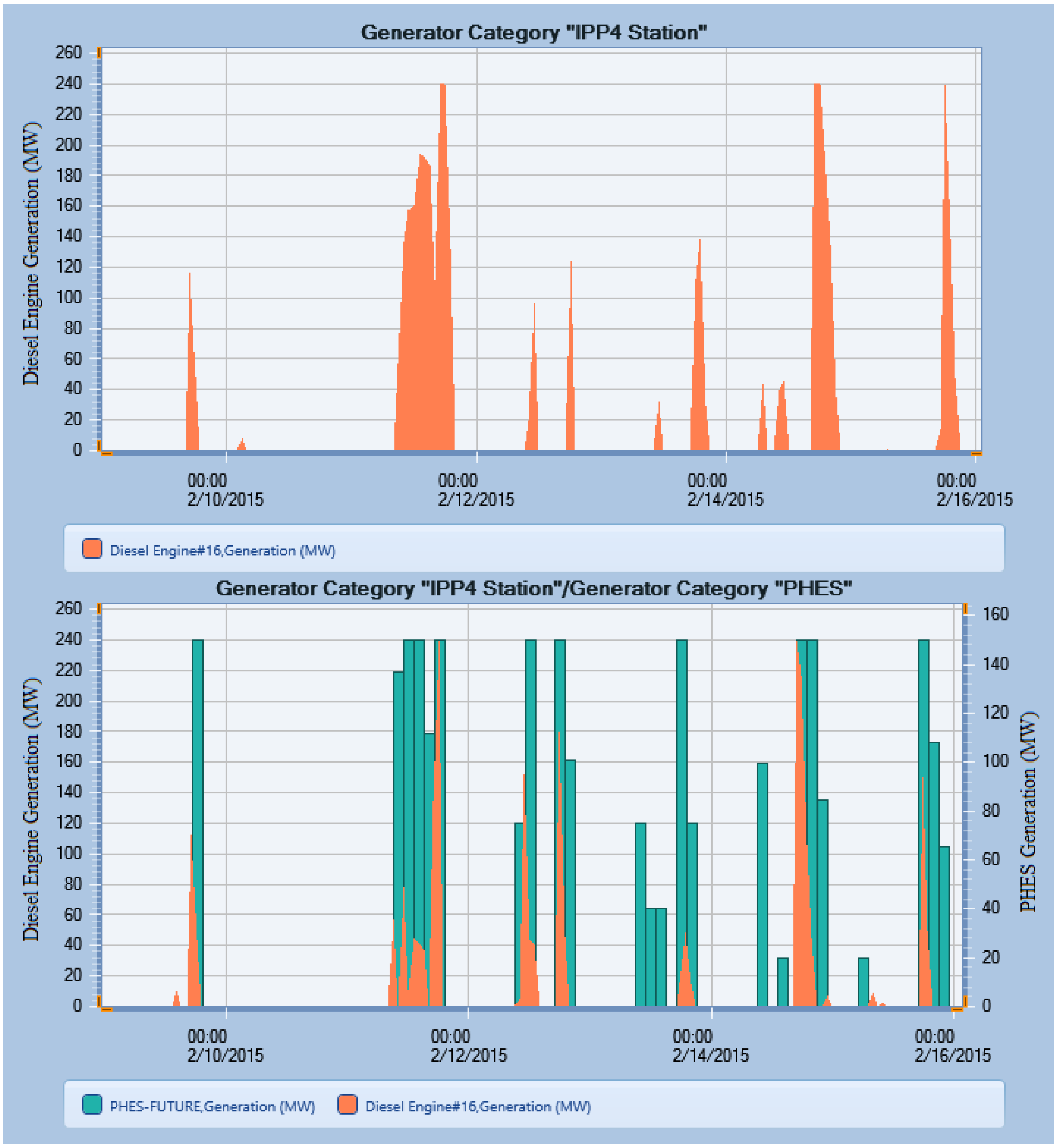

Figure 6.13: Generation of IPP4 for the two scenarios

Table 6.5 shows the generated power from all units in the whole practical model for the two scenarios. As indicated the wind integration level is increased after the PHES is included in the second scenario. The generation from the high efficiency units has been increased in the off-peak periods while the generation from the low efficiency units has been decreased in the peak periods.

Samra (1), Samra (2), Samra (3), Amman East and Qatrana these stations have the best efficiency and have the lower generation cost so their generation is increased.

Aqaba Thermal Station (1), Aqaba Thermal Station (2), Rehab station (2) and Hussein station, all these stations have low efficiency so their generation is reduced. IPP3 and IPP4 are diesel generators that have higher generation cost and, higher operation and maintenance cost, so their generation is reduced.

Table 6.5: Power generation for the two scenarios

Plant name	Unit #	Type of unit	Generation (GWh)	
			Without PHES	With PHES
Samra (1)	2	Combined Cycle	1959.281	2030.662
Samra (2)	2	Combined Cycle	1723.463	1794.227
Samra (3)	2	Combined Cycle	3478.637	3503.839
Samra (4)	1	Gas Turbine	237.419	173.962
Amman East	2	Combined Cycle	2710.418	2790.402
Amman South	1	Gas Turbine	0	0
Qatrana	2	Combined Cycle	3256.514	3267.841
IPP3	38	Diesel Engine	44.068	15.634
IPP4	16	Diesel Engine	185.824	109.429
Risha(1)	3	Gas Turbine	0	0
Risha (2)	2	Gas Turbine	0.060	0
Rehab (1)	2	Gas Turbine	0	0

Rehab (2)	2	Combined Cycle	989.798	986.980
Hussein	3	Steam	392.504	330.761
Aqaba Tharmal Station (1)	2	Steam	14.018	7.237
Aqaba Tharmal Station (2)	3	Steam	22.565	20.929
PHES	-	-	-	226.012
Wind farms	-	-	3742.199	3773.497

Table 6.6 provides the net saving in the total generation cost when the PHES is included. As indicated in the Table the annual total generation cost is reduced from 1015.919 million $ to 1008.682 million $ with a net saving of 7.236 million $.

Table 6.6: Total generation cost

Scenario	**Annual Total Generation Cost (Million $)**
Without PHES	1015.919
With PHES	1008.682
Saving $	7.236

As shown in table 6.5 the saving in total generation cost has been achieved through increasing in the wind integration level from 3742.199 GWh to 3773.497 GWh, increasing the total generation from the combined cycle units which have a higher generation efficiency (i.e , generation by Samra 3 station has been increased from 3478.637 GWh to 3503.839 GWh), the reduction of the total generation by the lower efficiency units (i.e, generation by Hussein station has been reduced from 392.504 GWh to 330.761 GWh) and the reduction of the total generation energy by the diesel engine units which have a higher operation and maintenance cost and higher fuel cost (i.e, IPP4 station has been reduced from 185.824 GWh to 109.429 GWh)

Figure 6.14 shows the total generation cost and wind integration level on a monthly basis of the practical system for the two scenarios. The inclusion of PHES unit into the system results in reduction in the overall generation cost and increasing the wind integration level over a period of one year. As shown in Figure 6.14 the saving in generation cost depends on the wind generation and demand load. The months which have higher wind power with lower demand load will make a significant reduction in the total generation cost as in months from January to May, November, and December.

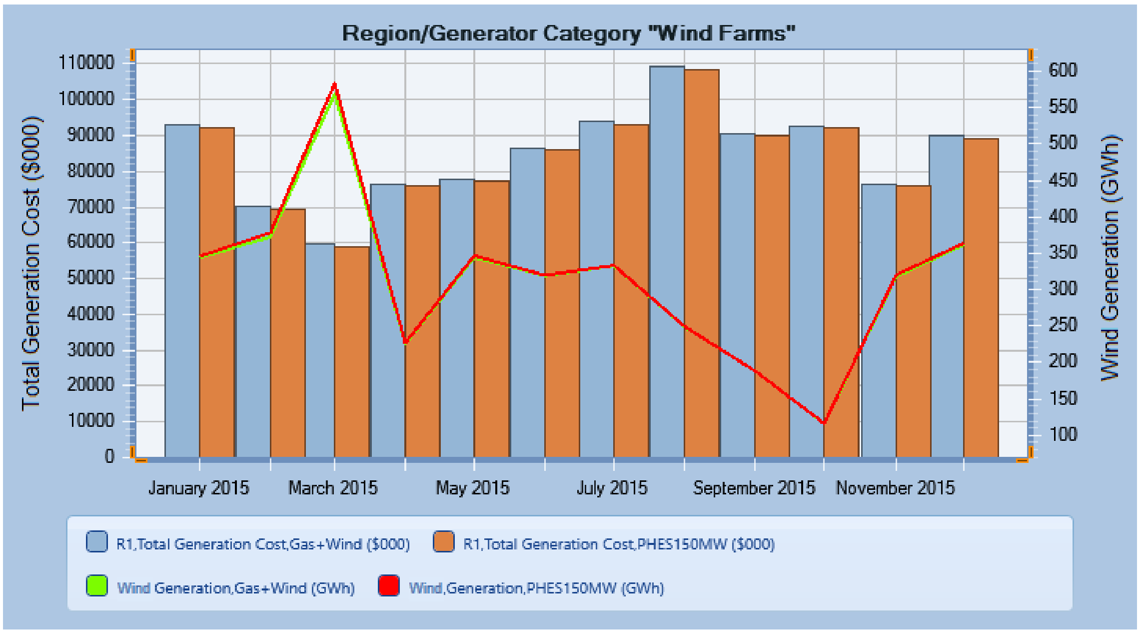

Figure 6.14: Total generation cost and wind generation on a monthly basis

Chapter Seven

Economic study

7.1 Introduction

The objective of this chapter is to provide a study related to the economic evaluation of connected PHES to power grid system along with a large integration of wind energy in Jordan.

Since there is no enough information about PHES costs, Economic analysis can be characterized by projecting the economic analysis of one of similar installed projects around the world that includes the consideration of capital and operational maintenance costs.

7.2 Overview of PHES cost

Notably, PHES systems are particularly cost effective at sites having high heads (large differences in elevation between the upper and lower reservoir). Having higher head requires less volume of water to store the same amount of energy. Therefore, resulting in smaller reservoir sizes, reduced civil works, smaller pump-turbine, motor-generator size and hence lower investment costs (Hayes, 2009).

PHES projects development costs are difficult to characterize in term of typical costs because it depends on the site conditions. The L/H ratio is a simple ratio used to measure the initial viability of a pumped storage project in siting level studies. L is the length of the waterway from the intake structure to the tailrace outlet and H is the gross head available for energy projects. Project site with an L/H ratio under 10 can be considered a promising pumped storage project since lower ratios will have lower cost in terms of specific cost of $/kW (Hayes, 2009).

Table 7.1 shows the specific cost $/kW and the total cost for many PHES stations in the world with respect to the L/H ratio and the rated capacity. As shown in Figure 7.2 it is cleared that the lower L/H ratio stations have the lower specific cost $/kW. Figure 7.1 shows the specific cost with respect to the rated capacity of PHES (Hayes, 2009).

Table 7.1: The Cost of PHES stations in united states with respect to L/H ratio (Hayes, 2009)

Project	**Initial Operation Year**	**Rated Capacity (MW)**	**L/H Ratio**	**Total Cost adjusted to 2009 $**	**Specific Cost Adjusted to 2009 $/kW**
Bad Creek	1991	1065	8.85	1,760,445,000	1,653
Bath County	1988	2100	8.20	2,643,543,000	1,259
Bear Swamp	1974	600	2.65	619,200,000	1,032
Blenheim-Gilboa	1973	1000	3.58	794,170,000	794
Cabin Creek	1967	300	3.87	215,775,000	719
Fairfield	1978	512	7.02	752,906,240	1,471
Helms	1981	1206	13.02	2,113,273,800	1,752
Jocasse	1973	610	5.26	533,213,200	874
Ludington	1973	1979	4.20	1,793,171,900	906
Muddy Run	1967	800	3.49	493,200,000	617
Northfield Mountain	1972	1080	8.45	870,696,000	806
Raccoon Mountain	1981	1530	3.90	1,008,790,200	659
Rocky Mountain	1990	760	4.79	986,221,600	1,298
Yards Creek	1965	360	5.03	233,496,000	649

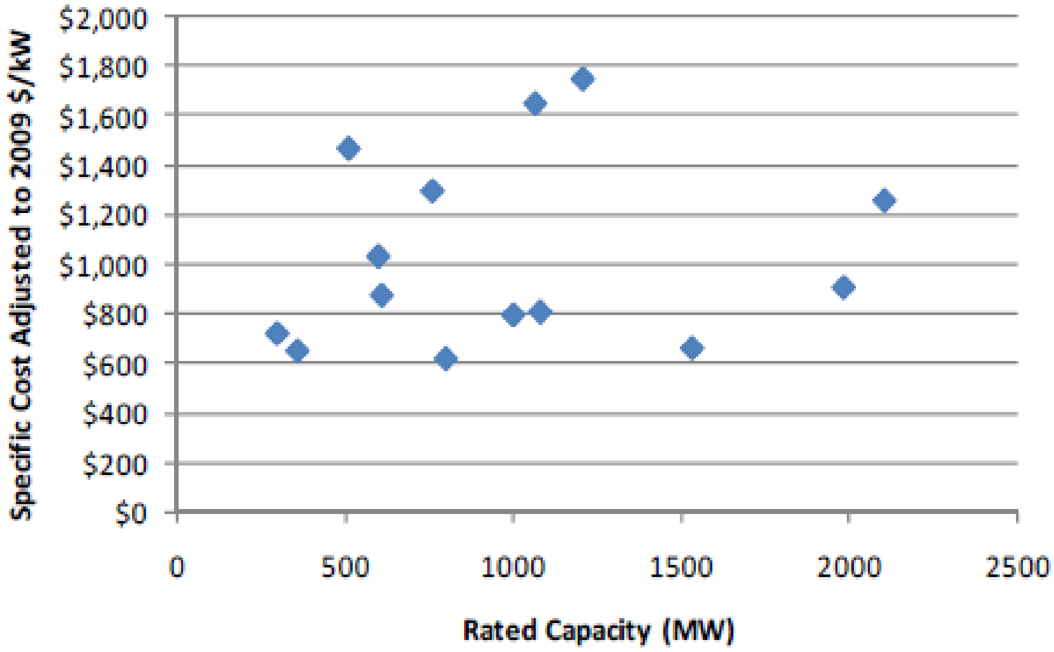

Figure 7.1: Specific cost of PHES stations $/kW with respect to rated capacity

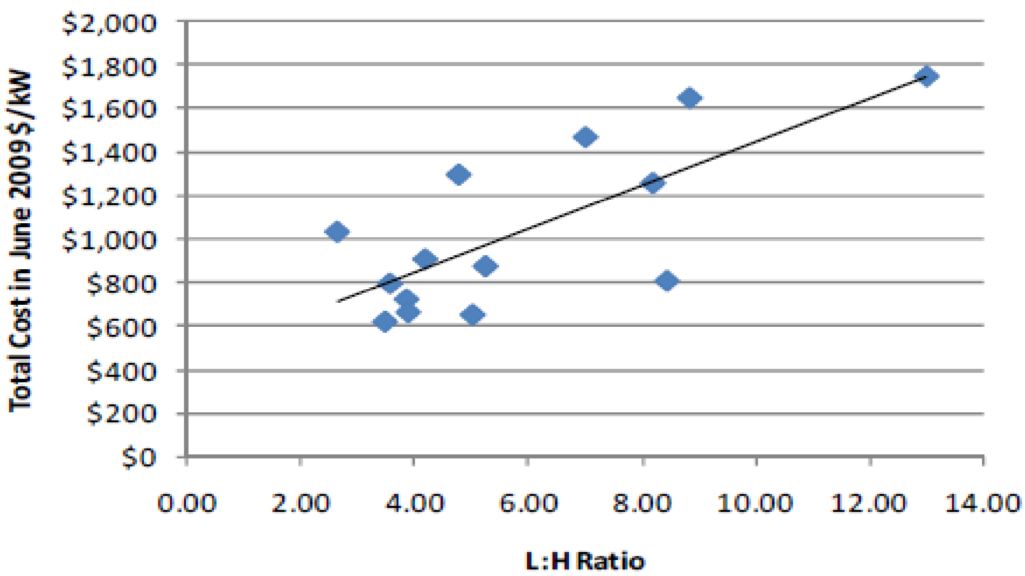

Figure 7.2: Specific cost of PHES stations $/kW with respect to L/H ratio

Operation and maintenance costs, like capital costs, are highly project dependent on specification and also depend on the owner’s philosophy with respect to maintenance. Table 7.2 provides the historical operation and maintenance costs for the same PHES stations (Hayes, 2009).

Table 7.2: Historical operation and maintenance cost of PHES stations

Project	**3-Year Average O&M Cost Adjusted to 2009 $/MWh**	**3-Year Average Number of Employees**
Bad Creek	3.41	8
Bath County	2.43	58
Bear Swamp	NR	NR
Blenheim-Gilboa	22.23	145
Cabin Creek	15.42	13
Fairfield	4.11	28
Helms	19.44	6
Jocasse	5.07	8
Ludington	5.55	41
Muddy Run	NR	NR
Northfield Mountain	NR	NR
Raccoon Mountain	19.86	36
Rocky Mountain	6.64	NR
Yards Creek	5.28	9

7.3 Capital cost estimate

In this project, the L/H ratio is found to be 4.2 (1500m/349m). Project site with an L:H ratio under 10 can be considered a promise pumped storage project. Therefore, resulting in smaller reservoir sizes, reduced civil works, smaller pump-turbine, motor-generator size and hence lower investment costs. So, the specific cost $/kW is considered to be at the range of 1000-1300 $/kW, and operation and maintenance cost is considered to be 5$/MWh.

By using the range of considered specific cost, the constructions cost for a 150 MW PHES is calculated to be at the range of 150,000,000 $ - 195,000,000 $.

By using the yearly savaging in the total system generation cost that obtained from previous chapter which is about (7,236,400 $), the simple payback period is found to be at the range of 20 to 26.9 year. It is within the acceptable range since the project life is more than 50 years.

Chapter Eight

Conclusions & Recommendations

8.1 Conclusions

This research has studied the impact of PHES inclusion in the power system along with the increasing of wind power integration level in Jordan. Three main aspects related to energy storage system design have been evaluated which are: conducting a location survey to examine the candidate sites for PHES installation in Jordan, design aspects of PHES station, simulating the practical power system module which includes thermal generating units, wind farms and PHES unit. This study has concluded the following issues:

- Jordan has a very promising potential to install PHES due to the achievement of the basic conditions for implementing such system.
- Ten dams have been analyzed by studying the geographical nature of the terrain nearby the dam. Also, a water balance for each dam has been studied to ensure that the water volume is always available when the dam drawn to minimum level.
- King Talal, Al-Wehdah, Wadi Al-Arab, Al-Tannur, Al-Mujib and Al-Walah dam, they all have achieved the basic requirements to install PHES.
- Al-Karamah, Ziglab, Shuib, and Al-Kafrien dam, none of them has met the basic requirements to install PHES due to the minimum available water value and the height difference are relatively small.
- Al-Tannur dam is selected as case study to design a PHES system for Jordan with a 150 MW nameplate capacity, 349 rated head and a 1.54 MCM upper reservoir

capacity. The upper reservoir has the storage capacity to generate rated power output continuously for 7.7 hours. The pumps can be operated continuously for 9.3 hours.

- The practical power system model has been designed by using PLEXOS software and solved by MOSEK 7.2 solver. The model includes all the thermal generating units and future wind farms. The model was executed through two scenarios with and without PHES unit. The relative gab for MOSEK has set to be 0.1 % which is the most accurate gab so the execution time is extended to 2 hours.
- The simulation results indicate that there is a reduction in the total generation cost for the whole power system with increasing on the wind integration level when the PHES is included as shown in Table 8.1.

Table 8.1: Total generation cost and wind generation level for one year

Scenario	**Annual Total Generation Cost (Million $)**	**Wind Generation (GWh)**
Without PHES	1015.919	3742.199
With PHES	1008.682	3773.497
Saving $	7.236	-
Increasing	-	31.298

- As indicated in Table 8.2, the inclusion of PHES unit not only has increased the generation from the high efficient generator in the low demand periods (off peak) but also decreased the generation from the low efficient and diesel generators at higher demand periods (peak). This is related to the operational approach of the PHES that is using the cheap energy to pump water within off peak hours when the high efficient generators and wind farms can meet the demand load. Then regenerate the stored energy when the high efficient generators and wind farms are not able to meet the demand load within peaks rather than operating the diesel and low efficient generators.

Table 8.2: Sample of power generation results

Generator	Type of unit	Generation (GWh)		Increasing (GWh)	Decreasing (GWh)
		Without PHES	With PHES		
IPP3	Diesel Engine	44.068	15.634	-	28.434
IPP4	Diesel Engine	185.824	109.429	-	76.395
Samra (3)	Combined Cycle	3478.637	3503.839	25.202	-
Qatrana	Combined Cycle	3256.514	3267.841	11.327	-

8.2 Recommendations

Jordan Suffers lack of energy resources besides the continuous growing in the demand load. Therefore, the clean and local energy resources such as wind energy is very important to meet the consumers' demand with lower cost and lower emissions. However, higher integration level of renewable energy sector particularly wind power may affect the stability of the national power grid. PHES offers the ability to solve this issue.

PHES system can enhance the energy sector by matching the power generation of the renewable energy resources with the demand load. That will lead to increase the integration level of renewable energy and reduce the total generating cost in the whole power system.

This research provided a clear study on the possibility of utilization of PHES in Jordan. Therefore, it is recommended to include PHES system in the national plan for the exploitation and development of the energy sector.

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APPENDICIES

Appendices

Appendix A: Sample of water balance data

Sample data of the water balance analysis for all dams in Jordan.

Table A.1: Water balance for Al-mujib dam

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
01-Jan-11	17.27668144	0	0.02156596
02-Jan-11	17.25511548	0	0.02155337
03-Jan-11	17.23356211	0	0.02154077
04-Jan-11	17.21202134	0	0.0215282
05-Jan-11	17.19049314	0	0.02151561
06-Jan-11	17.16897753	0	0.02150304
07-Jan-11	17.14747449	0	0.02149048
08-Jan-11	17.12598401	0	0.02147792
09-Jan-11	17.10450609	0	0.02146534
10-Jan-11	17.08304075	0	0.02145273
11-Jan-11	17.06158802	0	0.02144006
12-Jan-11	17.04014796	0	0.02142734
13-Jan-11	17.01872062	0	0.02141455
14-Jan-11	16.99730607	0	0.02140172
15-Jan-11	16.97590435	0	0.02138884
16-Jan-11	16.95451551	0	0.02137589
17-Jan-11	16.93313962	0	0.02136289
18-Jan-11	16.91177673	0	0.02134985
19-Jan-11	16.89042688	0	0.02133673
20-Jan-11	16.86909015	0	0.02132356

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
21-Jan-11	16.84776659	0	0.02131034
22-Jan-11	16.82645625	0	0.02129705
23-Jan-11	16.8051592	0	0.02177171
24-Jan-11	16.78338749	0	0.02078229
25-Jan-11	16.7626052	0	0.0212568
26-Jan-11	16.7413484	0	0.02124319
27-Jan-11	16.72010521	0	0.02122953
28-Jan-11	16.69887568	0	0.02121579
29-Jan-11	16.67765989	0	0.02120234
30-Jan-11	16.65645755	0	0.02118823
31-Jan-11	16.63526932	0.07421941	0
01-Feb-11	16.70948873	2.14064092	0
02-Feb-11	18.85012965	0.73625068	0
03-Feb-11	19.58638033	0.11443953	0
04-Feb-11	19.70081986	0.02292551	0
05-Feb-11	19.72374537	0.02293811	0
06-Feb-11	19.74668348	0.02295072	0
07-Feb-11	19.7696342	0	0
08-Feb-11	19.7696342	0	0
09-Feb-11	19.7696342	0	0
10-Feb-11	19.7696342	0	0
11-Feb-11	19.7696342	0.01148009	0
12-Feb-11	19.78111429	0	0
13-Feb-11	19.78111429	0	0.01148009
14-Feb-11	19.7696342	0	0.01147684
15-Feb-11	19.75815736	0	0.02294482
16-Feb-11	19.73521254	0	0.01146753
17-Feb-11	19.72374501	0	0.01146397
18-Feb-11	19.71228104	0	0.01146118
19-Feb-11	19.70081986	0	0.01145805
20-Feb-11	19.68936181	0	0.01145489
21-Feb-11	19.67790692	0.42593587	0
22-Feb-11	20.10384279	0.02314746	0

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
23-Feb-11	20.12699025	0.011579	0
24-Feb-11	20.13856925	0.03475501	0
25-Feb-11	20.17332426	0	0.0347552
26-Feb-11	20.13856906	0	0.02315405
27-Feb-11	20.11541501	0	0.02314122
28-Feb-11	20.09227379	0	0.02312841
01-Mar-11	20.06914538	0	0.02311605
02-Mar-11	20.04602933	0	0.02310241
03-Mar-11	20.02292692	0	0.02309009
04-Mar-11	19.99983683	0	0.02307734
05-Mar-11	19.97675949	0	0.02306463
06-Mar-11	19.95369486	0	0.02305191
07-Mar-11	19.93064295	0	0.02303922
08-Mar-11	19.90760373	0	0.0230264
09-Mar-11	19.88457733	0	0.02301433
10-Mar-11	19.861563	0	0.02300092
11-Mar-11	19.83856208	0	0.02298859
12-Mar-11	19.81557349	0	0.02297596
13-Mar-11	19.79259753	0	0.02296333
14-Mar-11	19.7696342	0	0.02295072
15-Mar-11	19.74668348	0	0.02293811
16-Mar-11	19.72374537	0	0.02292637
17-Mar-11	19.700819	0	0.02291208
18-Mar-11	19.67790692	0	0.02290035
19-Mar-11	19.65500657	0	0.0228878
20-Mar-11	19.63211877	0	0.02287524
21-Mar-11	19.60924353	0	0.02286272
22-Mar-11	19.58638081	0	0.02285059
23-Mar-11	19.56353022	0	0.02283727
24-Mar-11	19.54069295	0	0.03423307
25-Mar-11	19.50645988	0	0.03420498
26-Mar-11	19.4722549	0	0.02278773
27-Mar-11	19.44946717	0	0.0341583

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
28-Mar-11	19.41530887	0	0.03413031
29-Mar-11	19.38117856	0	0.0341018
30-Mar-11	19.34707676	0	0.03407576
31-Mar-11	19.313001	0	0.03404605

Table A.2: Water balance for Al-Tannur dam

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
1-Jan-11	8.1724	0	0
2-Jan-11	8.158	0	0.017594
3-Jan-11	8.1388	0	0.015648
4-Jan-11	8.1244	0	0.013106
5-Jan-11	8.11	0	0.010823
6-Jan-11	8.1004	0	0.011689
7-Jan-11	8.086	0	0.010914
8-Jan-11	8.0764	0	0.010672
9-Jan-11	8.0668	0	0.011153
10-Jan-11	8.0572	0	0.011286
11-Jan-11	8.0476	0	0.010467
12-Jan-11	8.038	0	0.011717
13-Jan-11	8.0284	0	0.01565
14-Jan-11	8.014	0	0.01678
15-Jan-11	7.9996	0	0.015368
16-Jan-11	7.99	0	0.015357
17-Jan-11	7.9756	0	0.016063
18-Jan-11	7.9612	0	0.019495
19-Jan-11	7.942	0	0.019708
20-Jan-11	7.9228	0	0.018962

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
21-Jan-11	7.9036	0	0.020379
22-Jan-11	7.8844	0	0.021221
23-Jan-11	7.8652	0	0.019367
24-Jan-11	7.846	0	0.017241
25-Jan-11	7.8268	0	0.017154
26-Jan-11	7.8124	0	0.016603
27-Jan-11	7.798	0	0.017187
28-Jan-11	7.7788	0	0.017751
29-Jan-11	7.7644	0	0.015958
30-Jan-11	7.7452	0	0.01623
31-Jan-11	7.7308	0	0.016908
1-Feb-11	7.726	1.0416	0.00141068
2-Feb-11	8.7676	0.0576	0.00346897
3-Feb-11	8.8252	0	0.000929441
4-Feb-11	8.8204	0	0.00133751
5-Feb-11	8.8156	0	0.0179001
6-Feb-11	8.7964	0	0.00211034
7-Feb-11	8.7868	0	0.00315752
8-Feb-11	8.782	0	0.0009789
9-Feb-11	8.782	0	0.0120679
10-Feb-11	8.7772	0	0.006804606
11-Feb-11	8.782	0.0048	0.0025246
12-Feb-11	8.83	0.048	0.00125235
13-Feb-11	8.8252	0	0.001254735
14-Feb-11	8.8204	0	0.00227505
15-Feb-11	8.8156	0	0.0025222
16-Feb-11	8.8156	0	0.003914942
17-Feb-11	9.1084	0.2928	0.001271
18-Feb-11	9.1516	0.0432	0.0028948
19-Feb-11	9.166	0.0144	0.001766584

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
20-Feb-11	9.1756	0.0096	0.003907344
21-Feb-11	9.8416	0.666	0.002058
22-Feb-11	10.0414	0.1998	0.002004
23-Feb-11	10.09	0.0486	0.001949
24-Feb-11	10.09	0	0.01376955
25-Feb-11	10.0846	0	0.016951739
26-Feb-11	10.0684	0	0.01811868
27-Feb-11	10.0576	0	0.018004
28-Feb-11	10.0414	0	0.017487
1-Mar-11	10.0252	2.4264	0.164091
2-Mar-11	10.009	0	0.01586
3-Mar-11	9.9928	0.000635	0.015565
4-Mar-11	9.982	0.000606	0.015594
5-Mar-11	9.9712	0.005068	0.015868
6-Mar-11	9.9604	0.00504	0.015797
7-Mar-11	9.955	0.002997	0.013797
8-Mar-11	9.9496	0.005674	0.011074
9-Mar-11	9.9442	0.004752	0.010907
10-Mar-11	9.9334	0.00712	0.013042
11-Mar-11	9.928	0.00148	0.014341
12-Mar-11	9.9172	0.00482	0.010305
13-Mar-11	9.9064	0.0018	0.01207
14-Mar-11	9.901	0.0022	0.010517
15-Mar-11	9.8902	0.0038	0.009208
16-Mar-11	9.874	0.0016	0.012533
17-Mar-11	9.8632	0.001728	0.012006
18-Mar-11	9.8524	0.001728	0.010838
19-Mar-11	9.8362	0.001728	0.01124
20-Mar-11	9.8254	0.001728	0.011813
21-Mar-11	9.8146	0.001728	0.014449

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
22-Mar-11	9.8038	0.001728	0.015385
23-Mar-11	9.793	0.001728	0.014375
24-Mar-11	9.7822	0.001728	0.012737
25-Mar-11	9.7714	0.001555	0.009731
26-Mar-11	9.766	0.001469	0.003622
27-Mar-11	9.7876	0.0216	0.012218
28-Mar-11	9.766	0.0013	0.019988
29-Mar-11	9.7498	0.00121	0.021172
30-Mar-11	9.7336	0.001123	0.020624
31-Mar-11	9.712	0.001037	0.020838
1-Apr-11	9.6958	0	0.020505
2-Apr-11	9.6742	0	0.020258
3-Apr-11	9.658	0	0.018982
4-Apr-11	9.6418	0.0756	0.007116
5-Apr-11	9.7174	0.0054	0.001307
6-Apr-11	9.7228	0.001037	0.00207
7-Apr-11	9.7228	0.000864	0.015018
8-Apr-11	9.7066	0.000864	0.020815
9-Apr-11	9.6904	0.000864	0.021219
10-Apr-11	9.6742	0.000691	0.021479
11-Apr-11	9.658	0.000518	0.017347
12-Apr-11	9.6418	0.000518	0.015853
13-Apr-11	9.6202	0	0.02298
14-Apr-11	9.5986	0	0.027068
15-Apr-11	9.577	0	0.027065
16-Apr-11	9.55	0	0.021596
17-Apr-11	9.5308	0	0.021101
18-Apr-11	9.5164	0	0.021089
19-Apr-11	9.4972	0	0.016814
20-Apr-11	9.4828	0	0.017326

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
21-Apr-11	9.4684	0	0.016679
22-Apr-11	9.454	0.024782	0.015182
23-Apr-11	9.4636	0	0.017651
24-Apr-11	9.4492	0	0.016257
25-Apr-11	9.4396	0	0.017317
26-Apr-11	9.4252	0	0.017949
27-Apr-11	9.4012	0	0.019861
28-Apr-11	9.3868	0	0.019687
29-Apr-11	9.3724	0	0.018945
30-Apr-11	9.3628	0	0.007675

Table A.3: Water balance for Al-Walah dam

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
01-Jan-11	1.947516	0	0.005699
02-Jan-11	1.941817	0	0.005699
03-Jan-11	1.936118	0	0.005699
04-Jan-11	1.930419	0	0.005699
05-Jan-11	1.92472	0	0.005699
06-Jan-11	1.919021	0	0.005699
07-Jan-11	1.913322	0	0.005699
08-Jan-11	1.907623	0	0.005699
09-Jan-11	1.901924	0	0.005699
10-Jan-11	1.896225	0	0.005699
11-Jan-11	1.890526	0	0.005699
12-Jan-11	1.884827	0	0.005699
13-Jan-11	1.879128	0	0.005699
14-Jan-11	1.873429	0	0.005699

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
15-Jan-11	1.86773	0	0.005699
16-Jan-11	1.862031	0	0.005699
17-Jan-11	1.856332	0	0.005699
18-Jan-11	1.850633	0	0.005699
19-Jan-11	1.844934	0	0.005699
20-Jan-11	1.839235	0	0.005699
21-Jan-11	1.833536	0	0.005699
22-Jan-11	1.827836	0	0.0057
23-Jan-11	1.822137	0	0.005699
24-Jan-11	1.816438	0	0.005699
25-Jan-11	1.810739	0	0.005699
26-Jan-11	1.80504	0	0.005699
27-Jan-11	1.799341	0	0.005699
28-Jan-11	1.793642	0	0.005699
29-Jan-11	1.787943	0	0.005699
30-Jan-11	1.782244	0.156724	0.005699
31-Jan-11	1.938968	0.019946	0
01-Feb-11	1.958914	0.872709	0
02-Feb-11	2.831623	0.497981	0
03-Feb-11	3.329604	0.007433	0
04-Feb-11	3.337037	0	0
05-Feb-11	3.337037	0.011149	0
06-Feb-11	3.348186	0	0
07-Feb-11	3.348186	0.037162	0
08-Feb-11	3.385348	0.148652	0
09-Feb-11	3.534	0	0
10-Feb-11	3.534	0.167232	0
11-Feb-11	3.701232	0.10034	0
12-Feb-11	3.801572	0.007432	0
13-Feb-11	3.809004	0	0

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
14-Feb-11	3.809004	0	0
15-Feb-11	3.801572	0	0.007432
16-Feb-11	3.790423	0	0.011149
17-Feb-11	3.779274	0	0.011149
18-Feb-11	3.768125	0	0.011149
19-Feb-11	3.756976	0	0.011149
20-Feb-11	3.745828	0.110249	0.011148
21-Feb-11	3.856077	0.877042	0
22-Feb-11	4.733119	0.01982	0
23-Feb-11	4.752939	0	0
24-Feb-11	4.743029	0	0.00991
25-Feb-11	4.733119	0	0.00991
26-Feb-11	4.713299	0	0.01982
27-Feb-11	4.688524	0	0.024775
28-Feb-11	4.663749	0	0.024775
01-Mar-11	4.643929	0	0.01982
02-Mar-11	4.629063	0	0.014866
03-Mar-11	4.609243	0	0.01982
04-Mar-11	4.594378	0	0.014865
05-Mar-11	4.579513	0	0.014865
06-Mar-11	4.564648	0	0.014865
07-Mar-11	4.544828	0	0.01982
08-Mar-11	4.525008	0	0.01982
09-Mar-11	4.505187	0	0.019821
10-Mar-11	4.485367	0	0.01982
11-Mar-11	4.460592	0	0.024775
12-Mar-11	4.435817	0	0.024775
13-Mar-11	4.411042	0	0.024775
14-Mar-11	4.391222	0	0.01982
15-Mar-11	4.376356	0	0.014866

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
16-Mar-11	4.361491	0	0.014865
17-Mar-11	4.346626	0	0.014865
18-Mar-11	4.331761	0	0.014865
19-Mar-11	4.316896	0	0.014865
20-Mar-11	4.302031	0	0.014865
21-Mar-11	4.287166	0	0.014865
22-Mar-11	4.272301	0	0.014865
23-Mar-11	4.257435	0	0.014866
24-Mar-11	4.24257	0	0.014865
25-Mar-11	4.227705	0	0.014865
26-Mar-11	4.21284	0	0.014865
27-Mar-11	4.197975	0	0.014865
28-Mar-11	4.18311	0	0.014865
29-Mar-11	4.168245	0	0.014865
30-Mar-11	4.148425	0	0.01982
31-Mar-11	4.128604	0	0.019821
01-Apr-11	4.108784	0	0.01982
02-Apr-11	4.088964	0	0.01982
03-Apr-11	4.069144	0	0.01982
04-Apr-11	4.049324	0	0.01982
05-Apr-11	4.029504	0	0.01982
06-Apr-11	4.014638	0	0.014866
07-Apr-11	3.999773	0	0.014865
08-Apr-11	3.989863	0	0.00991
09-Apr-11	3.979953	0	0.00991
10-Apr-11	3.970043	0	0.00991
11-Apr-11	3.955178	0	0.014865
12-Apr-11	3.940313	0	0.014865
13-Apr-11	3.925998	0	0.014315
14-Apr-11	3.910583	0	0.015415

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
15-Apr-11	3.895718	0	0.014865
16-Apr-11	3.880852	0	0.014866
17-Apr-11	3.865987	0	0.014865
18-Apr-11	3.851122	0	0.014865
19-Apr-11	3.836257	0	0.014865
20-Apr-11	3.823869	0	0.012388
21-Apr-11	3.812721	0	0.011148
22-Apr-11	3.801572	0	0.011149
23-Apr-11	3.790423	0	0.011149
24-Apr-11	3.779274	0	0.011149
25-Apr-11	3.768125	0	0.011149
26-Apr-11	3.756976	0	0.011149
27-Apr-11	3.742111	0	0.014865
28-Apr-11	3.730962	0	0.011149
29-Apr-11	3.72353	0	0.007432
30-Apr-11	3.712381	0	0.011149

Table A.4: Water balance for Al-Wehdah dam

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
01-Jan-11	6.644349827	0.020008	0.0045
02-Jan-11	6.659858347	0.020327	0.00479
03-Jan-11	6.675394917	0.030777	0.00482
04-Jan-11	6.701351631	0.025571	0.00475
05-Jan-11	6.722173285	0.02067	0.005021
06-Jan-11	6.737822413	0.020628	0.00495
07-Jan-11	6.753499771	0.025647	0.0047
08-Jan-11	6.774446891	0.020793	0.00505

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
09-Jan-11	6.79019026	0.020672	0.0049
10-Jan-11	6.805961979	0.01548	0.00495
11-Jan-11	6.816492226	0.015593	0.00505
12-Jan-11	6.8270351	0.015386	0.00483
13-Jan-11	6.837590613	0.015768	0.0052
14-Jan-11	6.848158773	0.015411	0.00483
15-Jan-11	6.858739593	0.012924	0.00498
16-Jan-11	6.866683523	0.010299	0.005
17-Jan-11	6.871983437	0.012976	0.00502
18-Jan-11	6.879939254	0.012813	0.00485
19-Jan-11	6.887902211	0.015629	0.005
20-Jan-11	6.898530599	0.013089	0.00511
21-Jan-11	6.906510231	0.013102	0.005115
22-Jan-11	6.914497017	0.013014	0.00502
23-Jan-11	6.922490962	0.010173276	0.00484
24-Jan-11	6.927824238	0.010287	0.00495
25-Jan-11	6.933160699	0.010469	0.00513
26-Jan-11	6.938500346	0.010423	0.00508
27-Jan-11	6.943843182	0.010436	0.00509
28-Jan-11	6.949189206	0.015842	0.00514
29-Jan-11	6.959890827	0.015684	0.00497
30-Jan-11	6.970605221	0.021096	0.005
31-Jan-11	6.986700783	0.020924	0.0048
01-Feb-11	7.002825146	0.015856	0.00509
02-Feb-11	7.013590738	0.015888	0.00511
03-Feb-11	7.024369157	0.021072	0.00488
04-Feb-11	7.04056086	0.135478	0.0049
05-Feb-11	7.171138731	0.104009	0.00485
06-Feb-11	7.270298153	0.09397	0.004939
07-Feb-11	7.359329271	2.533722	0.0049

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
08-Feb-11	9.888151178	0.282059	0.00495
09-Feb-11	10.16526047	0.098985	0.00529
10-Feb-11	10.25895535	0.063181	0.00519
11-Feb-11	10.31694563	0.041728	0.005356
12-Feb-11	10.35331839	0.019787	0.00521
13-Feb-11	10.3678953	0.034562	0.00536
14-Feb-11	10.39709685	0.027423	0.00548
15-Feb-11	10.41903983	0.01989	0.005242
16-Feb-11	10.43368842	0.056566	0.00517
17-Feb-11	10.48508425	0.027302	0.005215
18-Feb-11	10.50717103	0.027423	0.0053
19-Feb-11	10.52929386	0.027387	0.005228
20-Feb-11	10.55145279	0.042092	0.00508
21-Feb-11	10.58846466	0.08703	0.00525
22-Feb-11	10.67024507	0.057677	0.00538
23-Feb-11	10.72254154	0.050383	0.0054
24-Feb-11	10.76752506	0.027937	0.00539
25-Feb-11	10.79007162	0.035543	0.005424
26-Feb-11	10.8201906	0.058207	0.005342
27-Feb-11	10.87305564	0.0585	0.005435
28-Feb-11	10.9261207	0.066341	0.00545
01-Mar-11	10.9870121	0.051304	0.005463
02-Mar-11	11.03285305	0.043811	0.005497
03-Mar-11	11.071167	0.043996	0.005579
04-Mar-11	11.10958401	0.03628	0.005472
05-Mar-11	11.14039197	0.028886	0.005737
06-Mar-11	11.16354138	0.021117	0.005663
07-Mar-11	11.17899502	0.028736	0.005524
08-Mar-11	11.20220658	0.028802	0.005554
09-Mar-11	11.22545548	0.05984	0.005447

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
10-Mar-11	11.27984841	0.122615	0.00537
11-Mar-11	11.3970927	0.107753	0.005379
12-Mar-11	11.49946669	0.132436	0.00546
13-Mar-11	11.62644256	0.0774	0.0055
14-Mar-11	11.69834257	0.0617	0.00554
15-Mar-11	11.75450274	0.061949	0.00558
16-Mar-11	11.81087171	0.062163	0.005585
17-Mar-11	11.86745003	0.054263	0.0056
18-Mar-11	11.91611277	0.046295	0.005625
19-Mar-11	11.95678311	0.030051	0.005597
20-Mar-11	11.98123692	0.030147	0.005655
21-Mar-11	12.00572948	0.030227	0.005695
22-Mar-11	12.03026085	0.038266	0.005497
23-Mar-11	12.06302977	0.021987	0.005577
24-Mar-11	12.07944015	0.054172	0.004837
25-Mar-11	12.12877518	0.046754	0.005522
26-Mar-11	12.17000692	0.055267	0.005646
27-Mar-11	12.21962835	0.055594	0.005816
28-Mar-11	12.2694065	0.030822	0.005874
29-Mar-11	12.29435445	0.039472	0.006146
30-Mar-11	12.32767954	0.031069	0.00603
31-Mar-11	12.35271929	0.031129	0.00605
01-Apr-11	12.37779845	0.031725	0.006606
02-Apr-11	12.40291707	0.023257	0.006489
03-Apr-11	12.41968476	0.048055	0.006059
04-Apr-11	12.46168087	0.05629	0.00575
05-Apr-11	12.51222144	0.06404	0.004875
06-Apr-11	12.57138614	0.064473	0.005092
07-Apr-11	12.6307675	0.048295	0.005746
08-Apr-11	12.67331572	0.048551	0.005892

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
09-Apr-11	12.71597498	0.031592	0.005943
10-Apr-11	12.74162392	0.040077	0.005816
11-Apr-11	12.77588489	0.048708	0.005782
12-Apr-11	12.81881148	0.03142	0.00561
13-Apr-11	12.84462105	0.032142	0.006292
14-Apr-11	12.8704709	0.03209	0.0062
15-Apr-11	12.89636106	0.024043	0.00676
16-Apr-11	12.91364358	0.016324	0.007676
17-Apr-11	12.92229158	0.0095	0.0095
18-Apr-11	12.92229158	0.013828	0.009503
19-Apr-11	12.92661726	0.018165	0.00951
20-Apr-11	12.93527198	0.02199	0.009
21-Apr-11	12.9482625	0.026204	0.008867
22-Apr-11	12.96559892	0.040402	0.005675
23-Apr-11	13.00032574	0.031788	0.005696
24-Apr-11	13.02641814	0.024644	0.007226
25-Apr-11	13.04383562	0.03341	0.00725
26-Apr-11	13.06999569	0.165465	0.00765
27-Apr-11	13.22781146	0.231906	0.010271
28-Apr-11	13.4494464	0.211557	0.00512
29-Apr-11	13.65588321	0.180176	0.007795
30-Apr-11	13.82826361	0.144292	0.007015

Table A.5: Water balance for King Talal dam

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
01-Jan-11	22	0.880746	0.30157
02-Jan-11	23	0.27797	0.27797
03-Jan-11	23	0.281387	0.23657
04-Jan-11	23	0.255321	0.300138
05-Jan-11	23	0.255132	0.255132
06-Jan-11	23	0.264122	0.11473
07-Jan-11	23	0.277402	0.30728
08-Jan-11	23	1.249742	0.30857
09-Jan-11	24	0.453277	0.18437
10-Jan-11	24	0.27617	0.27617
11-Jan-11	24	0.258945	0.318702
12-Jan-11	24	0.254071	0.149496
13-Jan-11	24	0.263097	0.00913
14-Jan-11	25	0.266716	0.311534
15-Jan-11	25	0.32997	0.32997
16-Jan-11	25	0.263727	0.20397
17-Jan-11	25	0.27237	0.27237
18-Jan-11	25	0.260623	0.335319
19-Jan-11	25	0.256291	0.226413
20-Jan-11	25	0.256105	0.032016
21-Jan-11	25	0.266737	0.311555
22-Jan-11	25	0.276082	0.30596
23-Jan-11	25	0.276699	0.26176
24-Jan-11	25	0.268881	0.29876
25-Jan-11	25	0.250171	0.354745
26-Jan-11	25	0.253751	0.208934
27-Jan-11	25	0.254806	0.045656
28-Jan-11	25	0.266737	0.311555
29-Jan-11	25	0.588783	0.26012

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
30-Jan-11	25	1.439516	0.15227
31-Jan-11	27	1.131274	0.20257
01-Feb-11	27	0.7225	0.24267
02-Feb-11	28	0.356846	0.12467
03-Feb-11	28	0.269393	0.052695
04-Feb-11	28	0.42638	0.256118
05-Feb-11	29	1.25621	0.28107
06-Feb-11	30	0.329297	0.20547
07-Feb-11	30	0.382567	0.16587
08-Feb-11	30	0.260616	0.198702
09-Feb-11	30	0.258459	0.15011
10-Feb-11	30	0.427641	0.009724
11-Feb-11	30	0.268256	0.252778
12-Feb-11	30	0.275506	0.33742
13-Feb-11	30	0.275506	0.22907
14-Feb-11	30	0.256998	0.24152
15-Feb-11	30	0.247031	0.35538
16-Feb-11	30	0.261758	0.184366
17-Feb-11	30	0.255274	0.038576
18-Feb-11	31	0.260509	0.275988
19-Feb-11	31	0.2569	0.34977
20-Feb-11	31	0.824914	0.28317
21-Feb-11	31	0.470695	0.13017
22-Feb-11	31	0.260104	0.260104
23-Feb-11	31	0.252523	0.051304
24-Feb-11	32	0.257574	0.00992
25-Feb-11	32	0.261248	0.32316
26-Feb-11	32	0.25797	0.36632
27-Feb-11	32	0.266656	0.32857
28-Feb-11	32	0.252207	0.31412

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
01-Mar-11	32	0.265524	0.327438
02-Mar-11	32	0.253815	0.315728
03-Mar-11	31	0.263866	0.155518
04-Mar-11	32	0.26205	0.308485
05-Mar-11	32	0.2669	0.35977
06-Mar-11	31	0.300921	0.40927
07-Mar-11	31	0.306848	0.29137
08-Mar-11	31	0.321978	0.39937
09-Mar-11	31	0.353384	0.29147
10-Mar-11	31	0.591122	0.12677
11-Mar-11	32	0.595082	0.13073
12-Mar-11	32	0.31397	0.31397
13-Mar-11	32	0.320984	0.25907
14-Mar-11	32	0.299934	0.34637
15-Mar-11	32	0.255194	0.348064
16-Mar-11	32	0.250501	0.35885
17-Mar-11	32	0.252452	0.17506
18-Mar-11	32	0.250682	0.328074
19-Mar-11	32	0.24779	0.34066
20-Mar-11	32	0.252071	0.36042
21-Mar-11	32	0.2619	0.35477
22-Mar-11	32	0.253859	0.377687
23-Mar-11	32	0.245736	0.369563
24-Mar-11	32	0.368103	0.151405
25-Mar-11	32	0.290744	0.290744
26-Mar-11	32	0.250434	0.38974
27-Mar-11	32	0.25347	0.34634
28-Mar-11	31	0.237978	0.31537
29-Mar-11	31	0.256659	0.34953
30-Mar-11	31	0.244582	0.368409

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
31-Mar-11	31	0.250652	0.157781
01-Apr-11	31	0.244388	0.306302
02-Apr-11	31	0.247261	0.371088
03-Apr-11	31	0.251925	0.360274
04-Apr-11	31	0.295466	0.218074
05-Apr-11	31	0.25719	0.35006
06-Apr-11	31	0.256064	0.271543
07-Apr-11	31	0.247748	0.185834
08-Apr-11	31	0.243097	0.351446
09-Apr-11	31	0.248684	0.357033
10-Apr-11	31	0.25347	0.34634
11-Apr-11	31	0.247199	0.34007
12-Apr-11	31	0.237837	0.346185
13-Apr-11	31	0.227519	0.351347
14-Apr-11	30	0.227613	0.165699
15-Apr-11	30	0.219364	0.327713
16-Apr-11	30	0.212516	0.3673
17-Apr-11	30	0.225443	0.34927
18-Apr-11	30	0.208564	0.34787
19-Apr-11	30	0.21301	0.352315
20-Apr-11	30	0.209846	0.36463
21-Apr-11	30	0.219635	0.188678
22-Apr-11	30	0.22339	0.300782
23-Apr-11	30	0.219756	0.37454
24-Apr-11	29	0.226492	0.34032
25-Apr-11	29	0.218372	0.33672
26-Apr-11	29	0.208314	0.378577
27-Apr-11	29	0.222378	0.315248
28-Apr-11	29	0.236554	0.174641
29-Apr-11	29	0.230732	0.292645

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
30-Apr-11	29	0.230021	0.33837

Table A.6: Water balance for Wadi Al-Arab dam

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
1-Jan-11	3.783	0.041	0.004
2-Jan-11	3.82	0	0.005
3-Jan-11	3.815	0.009	0.004
4-Jan-11	3.82	0.12	0.004
5-Jan-11	3.936	0.055	0.004
6-Jan-11	3.987	0.06	0.004
7-Jan-11	4.043	0.07	0.004
8-Jan-11	4.109	0.103	0.004
9-Jan-11	4.208	0.056	0.004
10-Jan-11	4.26	0.033	0.004
11-Jan-11	4.289	0.032	0.004
12-Jan-11	4.317	0.033	0.004
13-Jan-11	4.346	0.033	0.004
14-Jan-11	4.375	0.032	0.004
15-Jan-11	4.403	0.029	0.004
16-Jan-11	4.428	0.105	0.004
17-Jan-11	4.529	0.033	0.004
18-Jan-11	4.558	0.033	0.004
19-Jan-11	4.587	0.034	0.004
20-Jan-11	4.617	0.033	0.004
21-Jan-11	4.646	0.033	0.004
22-Jan-11	4.675	0.034	0.004
23-Jan-11	4.705	0.033	0.004

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
24-Jan-11	4.734	0.034	0.004
25-Jan-11	4.764	0	0.005
26-Jan-11	4.759	0	0.005
27-Jan-11	4.754	0.019	0.004
28-Jan-11	4.769	0.048	0.004
29-Jan-11	4.813	0.034	0.004
30-Jan-11	4.843	0.139	0.004
31-Jan-11	4.978	0.079	0.004
1-Feb-11	5.053	0.029	0.004
2-Feb-11	5.078	0	0.005
3-Feb-11	5.073	0.004	0.004
4-Feb-11	5.073	0.212	0.004
5-Feb-11	5.281	0.106	0.004
6-Feb-11	5.383	0.097	0.004
7-Feb-11	5.476	0.249	0.004
8-Feb-11	5.721	0.104	0.004
9-Feb-11	5.821	0.094	0.004
10-Feb-11	5.911	0.078	0.004
11-Feb-11	5.985	0.095	0.004
12-Feb-11	6.076	0.095	0.004
13-Feb-11	6.167	0.096	0.004
14-Feb-11	6.259	0.063	0.004
15-Feb-11	6.318	0.032	0.004
16-Feb-11	6.346	0.031	0.004
17-Feb-11	6.373	0.031	0.004
18-Feb-11	6.4	0.031	0.004
19-Feb-11	6.427	0.032	0.004
20-Feb-11	6.455	0.036	0.004
21-Feb-11	6.487	0.103	0.004
22-Feb-11	6.586	0.093	0.004

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
23-Feb-11	6.675	0.092	0.004
24-Feb-11	6.763	0.093	0.004
25-Feb-11	6.852	0.094	0.004
26-Feb-11	6.942	0.094	0.004
27-Feb-11	7.032	0.094	0.004
28-Feb-11	7.122	0.078	0.004
1-Mar-11	7.196	0.061	0.004
2-Mar-11	7.253	0.032	0.004
3-Mar-11	7.281	0.033	0.004
4-Mar-11	7.31	0.032	0.004
5-Mar-11	7.338	0.033	0.004
6-Mar-11	7.367	0.033	0.004
7-Mar-11	7.396	0.032	0.004
8-Mar-11	7.424	0.033	0.004
9-Mar-11	7.453	0.183	0.004
10-Mar-11	7.632	0.196	0.004
11-Mar-11	7.824	0.122	0.004
12-Mar-11	7.942	0.0925	0.0045
13-Mar-11	8.03	0.0935	0.0045
14-Mar-11	8.119	0.0935	0.0045
15-Mar-11	8.208	0.088	0.005
16-Mar-11	8.291	0.0945	0.0045
17-Mar-11	8.381	0.0945	0.0045
18-Mar-11	8.471	0.0955	0.0045
19-Mar-11	8.562	0.0955	0.0045
20-Mar-11	8.653	0.0955	0.0045
21-Mar-11	8.744	0.0895	0.0045
22-Mar-11	8.829	0.0905	0.0045
23-Mar-11	8.915	0.0905	0.0045
24-Mar-11	9.001	0.0905	0.0045

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
25-Mar-11	9.087	0.0605	0.0045
26-Mar-11	9.143	0.0295	0.0045
27-Mar-11	9.168	0.0285	0.0045
28-Mar-11	9.192	0.0295	0.0045
29-Mar-11	9.217	0.0605	0.0045
30-Mar-11	9.273	0.0795	0.0045
31-Mar-11	9.348	0.0925	0.0045
1-Apr-11	9.436	0.0915	0.0045
2-Apr-11	9.523	0.0935	0.0045
3-Apr-11	9.612	0.0925	0.0045
4-Apr-11	9.7	0.1245	0.0045
5-Apr-11	9.82	0.1005	0.0045
6-Apr-11	9.916	0.0745	0.0045
7-Apr-11	9.986	0.0885	0.0045
8-Apr-11	10.07	0.0875	0.0045
9-Apr-11	10.153	0.0885	0.0045
10-Apr-11	10.237	0.0815	0.0045
11-Apr-11	10.314	0.084	0.006
12-Apr-11	10.392	0.084	0.006
13-Apr-11	10.47	0.085	0.006
14-Apr-11	10.549	0.084	0.006
15-Apr-11	10.627	0.085	0.006
16-Apr-11	10.706	0.085	0.006
17-Apr-11	10.785	0.085	0.006
18-Apr-11	10.864	0.085	0.006
19-Apr-11	10.943	0.086	0.006
20-Apr-11	11.023	0.085	0.006
21-Apr-11	11.102	0.08	0.006
22-Apr-11	11.176	0.0785	0.0055
23-Apr-11	11.249	0.08	0.006

Date	Reservoir Volume (MCM)	In Flow (MCM)	Out Flow (MCM)
24-Apr-11	11.323	0.073	0.006
25-Apr-11	11.39	0.08	0.006
26-Apr-11	11.464	0.08	0.006
27-Apr-11	11.538	0.074	0.006
28-Apr-11	11.606	0.0795	0.0055
29-Apr-11	11.68	0.102	0.006
30-Apr-11	11.776	0.094	0.006

Table A.7: Water balance for Ziglab dam

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
1-Jan-11	433,560	31,873	833
2-Jan-11	464,600	6,000	6,000
3-Jan-11	464,600	10,533	833
4-Jan-11	474,300	39,942	842
5-Jan-11	513,400	10,642	842
6-Jan-11	523,200	10,642	842
7-Jan-11	533,000	10,642	842
8-Jan-11	542,800	10,642	842
9-Jan-11	552,600	6,000	2,080
10-Jan-11	556,520	10,642	842
11-Jan-11	566,320	10,642	842
12-Jan-11	576,120	10,642	842
13-Jan-11	585,920	6,000	8,940
14-Jan-11	582,980	10,642	842
15-Jan-11	592,780	11,880	3,060
16-Jan-11	601,600	10,642	842

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
17-Jan-11	611,400	10,642	842
18-Jan-11	621,200	10,674	874
19-Jan-11	631,000	8,620	6,620
20-Jan-11	633,000	8,640	7,700
21-Jan-11	633,940	10,674	874
22-Jan-11	643,740	10,674	874
23-Jan-11	653,540	10,674	874
24-Jan-11	663,340	8,640	1,780
25-Jan-11	670,200	8,640	5,700
26-Jan-11	673,140	8,640	13,540
27-Jan-11	668,240	9,694	874
28-Jan-11	677,060	10,984	874
29-Jan-11	687,170	10,434	874
30-Jan-11	696,730	24,774	874
31-Jan-11	720,630	15,214	874
1-Feb-11	734,970	14,019	874
2-Feb-11	748,115	10,434	874
3-Feb-11	757,675	8,640	8,640
4-Feb-11	757,675	17,712	982
5-Feb-11	774,405	12,932	982
6-Feb-11	786,355	10,542	982
7-Feb-11	795,915	12,952	1,002
8-Feb-11	807,865	10,562	1,002
9-Feb-11	817,425	10,562	1,002
10-Feb-11	826,985	8,640	5,055
11-Feb-11	830,570	10,562	1,002
12-Feb-11	840,130	10,562	1,002
13-Feb-11	849,690	10,562	1,002
14-Feb-11	859,250	8,640	11,030

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
15-Feb-11	856,860	10,562	1,002
16-Feb-11	866,420	10,562	1,002
17-Feb-11	875,980	10,562	1,002
18-Feb-11	885,540	12,952	1,002
19-Feb-11	897,490	10,562	1,002
20-Feb-11	907,050	8,640	6,250
21-Feb-11	909,440	8,640	9,835
22-Feb-11	908,245	8,172	1,002
23-Feb-11	915,415	8,697	1,002
24-Feb-11	923,110	9,222	1,002
25-Feb-11	931,330	7,880	1,030
26-Feb-11	938,180	7,880	1,030
27-Feb-11	945,030	8,640	1,790
28-Feb-11	951,880	10,960	5,480
1-Mar-11	957,360	8,640	10,010
2-Mar-11	955,990	7,880	1,030
3-Mar-11	962,840	8,640	7,270
4-Mar-11	964,210	6,510	1,030
5-Mar-11	969,690	6,510	1,030
6-Mar-11	975,170	8,640	15,490
7-Mar-11	968,320	6,510	1,030
8-Mar-11	973,800	8,640	8,640
9-Mar-11	973,800	8,640	15,475
10-Mar-11	966,965	7,865	1,030
11-Mar-11	973,800	7,880	1,030
12-Mar-11	980,650	7,880	1,030
13-Mar-11	987,500	7,967	1,117
14-Mar-11	994,350	6,597	1,117
15-Mar-11	999,830	6,597	1,117

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
16-Mar-11	1,005,310	6,597	1,117
17-Mar-11	1,010,790	8,640	7,270
18-Mar-11	1,012,160	6,597	1,117
19-Mar-11	1,017,640	8,640	19,600
20-Mar-11	1,006,680	8,640	1,790
21-Mar-11	1,013,530	8,640	10,010
22-Mar-11	1,012,160	6,597	1,117
23-Mar-11	1,017,640	8,640	20,970
24-Mar-11	1,005,310	8,640	11,380
25-Mar-11	1,002,570	7,967	1,117
26-Mar-11	1,009,420	8,640	19,600
27-Mar-11	998,460	7,967	1,117
28-Mar-11	1,005,310	8,640	1,790
29-Mar-11	1,012,160	7,967	1,117
30-Mar-11	1,019,010	7,967	1,117
31-Mar-11	1,025,860	8,640	12,750
1-Apr-11	1,021,750	7,967	1,117
2-Apr-11	1,028,600	8,640	20,970
3-Apr-11	1,016,270	8,640	1,790
4-Apr-11	1,023,120	7,967	1,117
5-Apr-11	1,029,970	13,447	1,117
6-Apr-11	1,042,300	8,640	12,750
7-Apr-11	1,038,190	8,640	15,490
8-Apr-11	1,031,340	7,967	1,117
9-Apr-11	1,038,190	7,967	1,117
10-Apr-11	1,045,040	8,640	22,340
11-Apr-11	1,031,340	6,597	1,117
12-Apr-11	1,036,820	7,967	1,117
13-Apr-11	1,043,670	8,640	11,380

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
14-Apr-11	1,040,930	6,597	1,117
15-Apr-11	1,046,410	6,597	1,117
16-Apr-11	1,051,890	8,640	19,600
17-Apr-11	1,040,930	8,640	8,640
18-Apr-11	1,040,930	6,597	1,117
19-Apr-11	1,046,410	8,640	19,600
20-Apr-11	1,035,450	8,640	8,640
21-Apr-11	1,035,450	8,640	8,640
22-Apr-11	1,035,450	12,077	1,117
23-Apr-11	1,046,410	6,597	1,117
24-Apr-11	1,051,890	6,597	1,117
25-Apr-11	1,057,370	8,640	4,530
26-Apr-11	1,061,480	6,846	1,366
27-Apr-11	1,066,960	8,640	11,380
28-Apr-11	1,064,220	8,640	7,270
29-Apr-11	1,065,590	6,846	1,366
30-Apr-11	1,071,070	8,640	18,230

Table A.8: Water balance for Al-Karamah dam

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
1-Jan-11	18524997	0	0
2-Jan-11	18524997	0	0
3-Jan-11	18524997	0	0
4-Jan-11	18500824	0	24173
5-Jan-11	18500824	0	0
6-Jan-11	18500824	0	0

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
7-Jan-11	18500824	0	0
8-Jan-11	18500824	0	0
9-Jan-11	18500824	0	0
10-Jan-11	18500824	0	0
11-Jan-11	18500824	0	0
12-Jan-11	18476650	0	24174
13-Jan-11	18476650	0	0
14-Jan-11	18476650	0	0
15-Jan-11	18476650	0	0
16-Jan-11	18476650	0	0
17-Jan-11	18476650	0	0
18-Jan-11	18476650	0	0
19-Jan-11	18452477	0	24173
20-Jan-11	18452477	0	0
21-Jan-11	18452477	0	0
22-Jan-11	18452477	0	0
23-Jan-11	18452477	0	0
24-Jan-11	18452477	0	0
25-Jan-11	18428303	0	24174
26-Jan-11	18428303	0	0
27-Jan-11	18428303	0	0
28-Jan-11	18428303	0	0
29-Jan-11	18428303	0	0
30-Jan-11	18428303	0	0
31-Jan-11	18452477	0	0
1-Feb-11	18476650	24173	0
2-Feb-11	18476650	0	0
3-Feb-11	18476650	0	0
4-Feb-11	18476650	0	0
5-Feb-11	18476650	0	0

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
6-Feb-11	18476650	0	0
7-Feb-11	18476650	0	0
8-Feb-11	18476650	0	0
9-Feb-11	18452477	0	24173
10-Feb-11	18452477	0	0
11-Feb-11	18452477	0	0
12-Feb-11	18452477	0	0
13-Feb-11	18452477	0	0
14-Feb-11	18452477	0	0
15-Feb-11	18452477	0	0
16-Feb-11	18428303	0	24174
17-Feb-11	18428303	0	0
18-Feb-11	18428303	0	0
19-Feb-11	18428303	0	0
20-Feb-11	18428303	0	0
21-Feb-11	18428303	0	0
22-Feb-11	18500824	72521	0
23-Feb-11	18476650	0	24174
24-Feb-11	18476650	0	0
25-Feb-11	18476650	0	0
26-Feb-11	18476650	0	0
27-Feb-11	18476650	0	0
28-Feb-11	18452477	0	24173
1-Mar-11	18452477	0	0
2-Mar-11	18452477	0	0
3-Mar-11	18452477	0	0
4-Mar-11	18452477	0	0
5-Mar-11	18452477	0	0
6-Mar-11	18452477	0	0
7-Mar-11	18428303	0	24174

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
8-Mar-11	18428303	0	0
9-Mar-11	18428303	0	0
10-Mar-11	18428303	0	0
11-Mar-11	18452477	24174	0
12-Mar-11	18476650	24173	0
13-Mar-11	18476650	0	0
14-Mar-11	18476650	0	0
15-Mar-11	18452477	0	24173
16-Mar-11	18452477	0	0
17-Mar-11	18452477	0	0
18-Mar-11	18452477	0	0
19-Mar-11	18428303	0	24174
20-Mar-11	18428303	0	0
21-Mar-11	18404130	0	24173
22-Mar-11	18404130	0	0
23-Mar-11	18404130	0	0
24-Mar-11	18404130	0	0
25-Mar-11	18428303	24173	0
26-Mar-11	18428303	0	0
27-Mar-11	18428303	0	0
28-Mar-11	18404130	0	24173
29-Mar-11	18404130	0	0
30-Mar-11	18404130	0	0
31-Mar-11	18380260	0	23870
1-Apr-11	18380260	0	0
2-Apr-11	18380260	0	0
3-Apr-11	18380260	0	0
4-Apr-11	18380260	0	0
5-Apr-11	18380260	0	0
6-Apr-11	18380260	0	0

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
7-Apr-11	18356391	0	23869
8-Apr-11	18356391	0	0
9-Apr-11	18356391	0	0
10-Apr-11	18356391	0	0
11-Apr-11	18332521	0	23870
12-Apr-11	18332521	0	0
13-Apr-11	18332521	0	0
14-Apr-11	18332521	0	0
15-Apr-11	18332521	0	0
16-Apr-11	18308652	0	23869
17-Apr-11	18308652	0	0
18-Apr-11	18308652	0	0
19-Apr-11	18308652	0	0
20-Apr-11	18308652	0	0
21-Apr-11	18308652	0	0
22-Apr-11	18284782	0	23870
23-Apr-11	18284782	0	0
24-Apr-11	18284782	0	0
25-Apr-11	18284782	0	0
26-Apr-11	18260912	0	23870
27-Apr-11	18260912	0	0
28-Apr-11	18260912	0	0
29-Apr-11	18260912	0	0
30-Apr-11	18237043	0	23869

Table A.9: Water balance for Shuib dam

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
1-Jan-11	600,787	17,280	13,448
2-Jan-11	604,619	14,688	10,856
3-Jan-11	604,619	12,960	12,960
4-Jan-11	604,619	12,960	12,960
5-Jan-11	606,535	12,960	11,044
6-Jan-11	606,535	12,960	12,960
7-Jan-11	606,535	11,232	11,232
8-Jan-11	608,451	11,232	9,316
9-Jan-11	648,686	47,520	7,285
10-Jan-11	656,350	14,688	7,024
11-Jan-11	660,182	14,688	10,856
12-Jan-11	662,098	12,960	11,044
13-Jan-11	664,014	12,960	11,044
14-Jan-11	667,849	14,688	10,853
15-Jan-11	669,762	14,688	12,775
16-Jan-11	669,762	12,960	12,960
17-Jan-11	669,762	12,960	12,960
18-Jan-11	671,678	12,960	11,044
19-Jan-11	671,678	12,960	12,960
20-Jan-11	671,678	12,960	12,960
21-Jan-11	673,594	12,960	11,044
22-Jan-11	673,594	12,960	12,960
23-Jan-11	673,594	12,960	12,960
24-Jan-11	658,266	7,776	23,104
25-Jan-11	639,106	6,912	26,072
26-Jan-11	629,527	6,912	16,491
27-Jan-11	619,947	6,912	16,492
28-Jan-11	600,787	5,616	24,776
29-Jan-11	600,787	5,616	5,616

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
30-Jan-11	581,627	5,616	24,776
31-Jan-11	784,929	216,000	12,698
1-Feb-11	906,401	138,240	16,768
2-Feb-11	978,674	82,080	9,807
3-Feb-11	981,123	17,280	14,831
4-Feb-11	981,123	12,960	12,960
5-Feb-11	966,428	17,280	31,975
6-Feb-11	941,936	17,280	41,772
7-Feb-11	917,444	17,280	41,772
8-Feb-11	917,444	17,280	17,280
9-Feb-11	913,027	17,280	21,697
10-Feb-11	906,401	15,552	22,178
11-Feb-11	906,401	15,552	15,552
12-Feb-11	899,775	15,552	22,178
13-Feb-11	899,775	15,552	15,552
14-Feb-11	893,149	15,552	22,178
15-Feb-11	877,689	13,824	29,284
16-Feb-11	855,603	13,824	35,910
17-Feb-11	840,143	13,824	29,284
18-Feb-11	818,057	13,824	35,910
19-Feb-11	807,014	13,824	24,867
20-Feb-11	800,389	12,960	19,585
21-Feb-11	800,389	21,600	21,600
22-Feb-11	802,598	21,600	19,391
23-Feb-11	798,181	15,552	19,969
24-Feb-11	793,763	15,552	19,970
25-Feb-11	789,346	15,552	19,969
26-Feb-11	784,929	15,552	19,969
27-Feb-11	784,929	12,960	12,960
28-Feb-11	784,929	12,960	12,960

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
1-Mar-11	780,512	10,368	14,845
2-Mar-11	762,843	10,368	28,037
3-Mar-11	749,591	10,368	23,620
4-Mar-11	749,591	10,368	10,368
5-Mar-11	749,591	10,368	10,368
6-Mar-11	747,383	8,640	10,848
7-Mar-11	747,383	8,640	8,640
8-Mar-11	747,383	7,776	7,776
9-Mar-11	747,383	7,776	7,776
10-Mar-11	762,843	25,920	10,460
11-Mar-11	773,886	25,920	14,877
12-Mar-11	776,095	17,280	15,071
13-Mar-11	776,095	10,368	10,368
14-Mar-11	778,303	10,368	8,160
15-Mar-11	778,303	10,368	10,368
16-Mar-11	776,095	10,368	12,576
17-Mar-11	773,886	9,936	12,145
18-Mar-11	771,677	9,936	12,145
19-Mar-11	771,677	9,936	9,936
20-Mar-11	767,260	8,640	13,057
21-Mar-11	756,217	7,776	18,819
22-Mar-11	745,174	7,776	18,819
23-Mar-11	731,923	7,776	21,027
24-Mar-11	729,714	12,960	15,169
25-Mar-11	736,340	21,600	14,974
26-Mar-11	736,340	16,416	16,416
27-Mar-11	731,923	9,504	13,921
28-Mar-11	723,088	9,504	18,339
29-Mar-11	709,837	8,640	21,891
30-Mar-11	696,585	8,640	21,892

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
31-Mar-11	692,753	8,640	12,472
1-Apr-11	687,005	8,640	14,388
2-Apr-11	681,257	8,640	14,388
3-Apr-11	677,425	8,640	12,472
4-Apr-11	673,594	8,640	12,471
5-Apr-11	673,594	15,552	15,552
6-Apr-11	675,510	14,688	12,772
7-Apr-11	673,594	13,824	15,740
8-Apr-11	671,678	12,960	14,876
9-Apr-11	667,846	12,960	16,792
10-Apr-11	658,266	10,368	19,948
11-Apr-11	648,686	8,640	18,220
12-Apr-11	639,106	8,640	18,220
13-Apr-11	641,022	21,600	19,684
14-Apr-11	635,275	12,960	18,707
15-Apr-11	631,443	7,776	11,608
16-Apr-11	619,947	7,776	19,272
17-Apr-11	610,367	7,776	17,356
18-Apr-11	602,703	7,776	15,440
19-Apr-11	591,207	6,912	18,408
20-Apr-11	581,627	6,912	16,492
21-Apr-11	564,384	6,048	23,291
22-Apr-11	550,972	6,048	19,460
23-Apr-11	539,477	6,048	17,543
24-Apr-11	527,981	6,048	17,544
25-Apr-11	504,985	6,048	29,044
26-Apr-11	496,820	5,616	13,781
27-Apr-11	488,650	5,616	13,786
28-Apr-11	480,461	5,184	13,373
29-Apr-11	472,311	5,184	13,334

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
30-Apr-11	464,142	5,184	13,353

Table A.10: Water balance for Al-Kafreen dam

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
1-Jan-11	1,730,349	46,542	11,730
2-Jan-11	1,743,404	30,240	17,185
3-Jan-11	1,747,755	25,920	21,569
4-Jan-11	1,752,107	21,600	17,248
5-Jan-11	1,756,458	21,600	17,249
6-Jan-11	1,765,161	21,600	12,897
7-Jan-11	1,765,161	18,144	18,144
8-Jan-11	1,769,513	18,974	14,622
9-Jan-11	1,830,434	75,600	14,679
10-Jan-11	1,843,488	21,600	8,546
11-Jan-11	1,852,191	21,600	12,897
12-Jan-11	1,856,543	19,872	15,520
13-Jan-11	1,860,894	19,872	15,521
14-Jan-11	1,865,246	19,872	15,520
15-Jan-11	1,873,949	19,872	11,169
16-Jan-11	1,878,300	19,008	14,657
17-Jan-11	1,887,003	19,008	10,305
18-Jan-11	1,895,706	19,008	10,305
19-Jan-11	1,900,058	19,008	14,656
20-Jan-11	1,900,058	19,008	19,008
21-Jan-11	1,908,761	19,008	10,305
22-Jan-11	1,913,112	19,008	14,657
23-Jan-11	1,917,464	19,008	14,656

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
24-Jan-11	1,913,112	14,688	19,040
25-Jan-11	1,913,112	14,688	14,688
26-Jan-11	1,908,761	14,688	19,039
27-Jan-11	1,913,112	14,688	10,337
28-Jan-11	1,908,761	14,256	18,607
29-Jan-11	1,913,112	14,699	10,348
30-Jan-11	1,913,112	16,475	16,475
31-Jan-11	2,129,581	229,256	12,787
1-Feb-11	2,298,183	186,359	17,757
2-Feb-11	2,588,115	306,058	16,126
3-Feb-11	2,604,894	38,880	22,101
4-Feb-11	2,604,894	25,920	25,920
5-Feb-11	2,593,708	37,192	48,378
6-Feb-11	2,582,522	34,560	45,746
7-Feb-11	2,571,337	34,560	45,745
8-Feb-11	2,571,337	39,403	39,403
9-Feb-11	2,565,744	38,880	44,473
10-Feb-11	2,560,151	34,560	40,153
11-Feb-11	2,571,337	39,402	28,216
12-Feb-11	2,582,522	38,880	27,695
13-Feb-11	2,582,522	38,880	38,880
14-Feb-11	2,588,115	38,880	33,287
15-Feb-11	2,588,115	34,560	34,560
16-Feb-11	2,582,522	34,560	40,153
17-Feb-11	2,576,929	34,560	40,153
18-Feb-11	2,582,522	36,288	30,695
19-Feb-11	2,582,522	34,560	34,560
20-Feb-11	2,576,929	32,832	38,425
21-Feb-11	2,582,522	38,880	33,287
22-Feb-11	2,588,115	38,880	33,287

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
23-Feb-11	2,588,115	35,424	35,424
24-Feb-11	2,593,708	34,560	28,967
25-Feb-11	2,593,708	34,560	34,560
26-Feb-11	2,588,115	34,560	40,153
27-Feb-11	2,582,522	32,832	38,425
28-Feb-11	2,582,522	32,832	32,832
1-Mar-11	2,576,929	30,240	35,833
2-Mar-11	2,571,337	26,784	32,376
3-Mar-11	2,565,744	25,920	31,513
4-Mar-11	2,565,744	25,920	25,920
5-Mar-11	2,565,744	25,920	25,920
6-Mar-11	2,560,151	24,192	29,785
7-Mar-11	2,560,151	24,192	24,192
8-Mar-11	2,560,151	24,192	24,192
9-Mar-11	2,554,558	24,192	29,785
10-Mar-11	2,576,929	51,840	29,469
11-Mar-11	2,593,708	51,840	35,061
12-Mar-11	2,599,301	30,240	24,647
13-Mar-11	2,599,301	24,192	24,192
14-Mar-11	2,593,708	21,600	27,193
15-Mar-11	2,593,708	21,600	21,600
16-Mar-11	2,588,115	20,736	26,329
17-Mar-11	2,582,522	20,736	26,329
18-Mar-11	2,576,929	20,736	26,329
19-Mar-11	2,576,929	20,736	20,736
20-Mar-11	2,571,337	19,008	24,600
21-Mar-11	2,565,744	17,280	22,873
22-Mar-11	2,554,558	17,280	28,466
23-Mar-11	2,543,372	17,547	28,733
24-Mar-11	2,543,372	22,640	22,640

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
25-Mar-11	2,565,744	45,120	22,748
26-Mar-11	2,571,337	27,648	22,055
27-Mar-11	2,565,744	20,736	26,329
28-Mar-11	2,554,558	20,736	31,922
29-Mar-11	2,543,372	19,008	30,194
30-Mar-11	2,532,186	17,280	28,466
31-Mar-11	2,532,186	17,280	17,280
1-Apr-11	2,532,186	17,280	17,280
2-Apr-11	2,532,186	17,280	17,280
3-Apr-11	2,526,593	17,280	22,873
4-Apr-11	2,521,000	17,280	22,873
5-Apr-11	2,554,558	60,820	27,262
6-Apr-11	2,565,744	34,560	23,374
7-Apr-11	2,571,337	30,240	24,647
8-Apr-11	2,576,929	30,240	24,648
9-Apr-11	2,576,929	25,920	25,920
10-Apr-11	2,571,337	24,192	29,784
11-Apr-11	2,560,151	24,192	35,378
12-Apr-11	2,560,151	24,192	24,192
13-Apr-11	2,565,744	30,240	24,647
14-Apr-11	2,565,744	25,920	25,920
15-Apr-11	2,571,337	25,920	20,327
16-Apr-11	2,554,558	21,600	38,379
17-Apr-11	2,548,965	21,600	27,193
18-Apr-11	2,543,372	21,600	27,193
19-Apr-11	2,543,372	21,600	21,600
20-Apr-11	2,537,779	20,736	26,329
21-Apr-11	2,532,186	20,736	26,329
22-Apr-11	2,504,221	20,736	48,701
23-Apr-11	2,487,443	20,736	37,514

Date	Reservoir Volume m^3	In Flow m^3	Out Flow m^3
24-Apr-11	2,481,850	19,008	24,601
25-Apr-11	2,459,478	15,552	37,924
26-Apr-11	2,442,699	15,552	32,331
27-Apr-11	2,433,065	14,688	24,322
28-Apr-11	2,408,979	13,824	37,910
29-Apr-11	2,394,527	13,824	28,276
30-Apr-11	2,389,710	13,824	18,641

Appendix B: Load and wind data

Table B.1: Sample of load data

Year	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015
Month	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
Day	1	2	3	4	5	6	7	8	9	10
Hours	Load (MW)									
1	2010	1870	1964	1991	2011	1951	1932	1948	1838	1952
2	1827	1699	1767	1772	1805	1772	1734	1766	1663	1747
3	1666	1577	1644	1654	1658	1652	1614	1632	1544	1625
4	1545	1480	1560	1570	1590	1590	1530	1540	1460	1560
5	1569	1524	1583	1624	1641	1612	1575	1553	1494	1586
6	1671	1647	1779	1810	1816	1801	1762	1652	1622	1755
7	1647	1675	1963	1975	1997	1951	1882	1622	1659	1842
8	1623	1730	2166	2178	2186	2106	2032	1606	1753	1990
9	1803	1967	2403	2392	2348	2267	2203	1755	2004	2212
10	2120	2317	2599	2529	2483	2407	2313	2001	2274	2385
11	2496	2651	2775	2702	2604	2488	2408	2326	2488	2552
12	2820	2898	2983	2840	2740	2560	2510	2650	2669	2630
13	2716	3090	3110	2811	2697	2495	2463	2600	2740	2574
14	2691	3006	3028	2808	2685	2468	2451	2559	2685	2520
15	2662	3028	3036	2846	2705	2494	2484	2560	2687	2509
16	2643	2988	3018	2806	2681	2461	2480	2552	2650	2491
17	2701	3006	3052	2852	2718	2553	2595	2603	2673	2546
18	2830	3120	3180	3080	3020	2930	2790	2750	2920	2890
19	2627	2975	2977	2941	2884	2807	2641	2587	2815	2770
20	2521	2846	2830	2825	2764	2679	2515	2502	2675	2641
21	2466	2778	2755	2765	2695	2621	2447	2468	2596	2596
22	2351	2642	2657	2659	2583	2518	2378	2390	2484	2493
23	2232	2491	2453	2481	2419	2373	2275	2240	2371	2343
24	2050	2228	2245	2251	2179	2172	2134	2037	2175	2148

Table B.2: Sample of reference wind generation data

Year	2016	2016	2016	2016	2016	2016	2016	2016	2016	2016
Month	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan
Day	1	2	3	4	5	6	7	8	9	10
Hours	Generation (MW)									
1	16.69	0.00	18.07	0.61	7.29	99.63	47.66	75.35	114.66	29.56
2	4.36	0.64	11.10	1.21	10.12	98.25	53.16	67.70	114.46	27.05
3	0.00	0.92	9.15	2.27	16.09	98.60	92.76	82.40	114.60	16.18
4	1.18	3.70	7.14	0.00	23.57	101.49	91.71	90.01	114.56	25.62
5	0.30	9.67	6.76	0.00	23.96	102.88	96.45	96.41	114.29	32.90
6	4.35	19.93	2.28	0.00	27.73	100.12	109.50	102.06	114.70	54.50
7	10.82	20.51	0.94	0.00	38.44	99.38	111.06	97.27	114.62	62.60
8	17.68	9.33	0.00	0.00	56.79	91.96	99.80	101.86	114.10	71.75
9	21.78	3.71	0.00	0.00	73.11	60.20	97.45	96.84	113.81	67.58
10	31.26	3.81	0.00	0.00	76.44	31.93	78.71	111.19	110.40	73.33
11	18.52	2.01	0.00	2.09	83.04	26.60	81.10	109.99	111.26	67.78
12	18.82	2.63	0.00	0.04	88.65	9.10	89.64	92.30	111.97	57.41
13	10.76	6.75	0.00	0.00	87.68	8.41	88.66	96.30	110.93	44.37
14	5.00	5.76	0.00	2.52	87.31	19.49	78.60	106.30	109.85	63.90
15	0.81	10.52	0.00	2.46	82.63	20.46	66.39	107.94	101.71	79.39
16	0.00	14.44	0.00	1.09	74.26	7.14	69.53	113.54	90.46	54.11
17	0.00	10.99	0.00	6.45	62.93	2.88	59.83	113.99	71.82	38.26
18	0.00	14.92	0.81	7.39	55.91	9.51	36.06	114.47	57.12	37.13
19	0.00	23.47	5.19	6.20	72.86	6.07	41.89	114.07	27.38	34.71
20	0.00	23.85	7.04	4.36	93.49	14.52	59.42	114.73	11.16	28.40
21	0.00	19.23	6.93	1.52	89.41	20.94	67.09	114.44	7.80	6.58
22	0.00	20.04	5.02	0.00	90.30	26.20	54.01	114.73	10.18	2.44
23	0.33	17.89	0.94	1.68	101.40	66.20	67.05	114.18	7.29	8.04
24	0.01	21.91	0.95	5.48	101.83	65.09	69.71	114.47	15.97	7.23

تصميم نظام التخزين الكهرومائي للطاقة في الأردن

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ملخص

أصبحت الطاقة من المصادر المتجددة، وخاصة طاقة الرياح منتشرة بشكل كبير في جميع أنحاء العالم. تعتبر الأردن واحدة من الدول التي تهتم في زيادة مستوى الاعتماد على طاقة الرياح المربوطة على شبكة الكهرباء الوطنية. العيب الرئيسي لطاقة الرياح هو أنها تعتبر مصدر غير ثابت ومتغير بشكل كبير لذلك طاقة الرياح مصدر يصعب التحكم به مع الطلب على الطاقة. يعتبر نظام تخزين الطاقة الكهرومائي حل مناسب جدا لموازنة الطاقة المولدة من محطات الرياح وتخزينها. في هذه الدراسة تمثل السدود الأحواض المنخفضة لنظام التخزين الكهرومائي دون أن يؤثر ذلك على آلية عمل هذه السدود أو الأهداف التي انشئت من أجلها كذلك يتم تزويد دراسة عن المناطق المرشحة كأحواض علوية لنظام التخزين الكهرومائي. هذه الأحواض العليا هي أحواض شبه طبيعية لا تحتاج لتكلفة انشائية عالية ، أي أقل تكلفة نسبيا كما هو مبين في التحليل الاقتصادي لتنفيذ هذا المشروع.

تم تصميم جميع أنظمة الطاقة من كل من الطاقة التقليدية والمتجددة في الأردن باستخدام حزمة برامج (PLEXOS). تم استخدام تقنية (Mixed Integer Programing) لتحقيق الحل الأمثل لتغير طاقة الرياح. تم تصميم نموذج القدرة باستخدام الخصائص الفعلية لجميع وحدات توليد الطاقة في الأردن. تم استخدام بيانات معدل الطلب الحقيقي على الطاقة من شركة الكهرباء الوطنية بحيث توفر الدراسة حل واقعي لتقلب مصادر الطاقة المتجددة خاصة طاقة الرياح. تم الحصول على سرعة الرياح لمدة سنة واحدة لمرتفعات الطفيلة وتنفيذها في نموذج التصميم. يتم إجراء تحليل لأنظمة الطاقة مع وبدون نظام التخزين الكهرومائي لإظهار التحسينات التي يتم تحقيقها باستخدام نظام التخزين هذا.

تم إجراء مسح موقعي للمواقع المرشحة في الأردن حيث يمكن تشييد وتشغيل نظام التخزين الكهرومائي (PHES) بطريقة فعالة. تم دراسة و تحليل عشرة مواقع مرشحة في الأردن. وتبين النتائج أن ستة منها تعتبر مواقع مناسبة لتثبيت وتشغيل نظام تخزين الطاقة الكهرومائي. وقد تم اختيار سد التنور لتصميم هذا النظام في الأردن. بعد تصميم و تشغيل نموذج الطاقة من خلال سيناريوهات مختلفة ، يمكن ملاحظة التأثير الإيجابي على سلوك نظام الطاقة عندما يتم تضمين نظام التخزين، تم زيادة نسبة التوليد من توربينات الرياح كذلك التوليد اصبح متزامن مع الطلب على الطاقة وتقلص معدل توليد الطاقة في فترة الذروة من قبل الوحدات المكلفة غير الفعالة، وبالتالي تقلص إجمالي تكلفة التوليد.