Optimal Design of a Solar Water Pumping System with Hybrid Storage for a Site in Iran

by

©Amirhossein Jahanfar

A thesis submitted to the School of Graduate Studies in partial fulfillment of
the requirements for the degree of

Master of Engineering

Faculty of Engineering and Applied Science
Memorial University of Newfoundland

December 2022

St. John’s, Newfoundland, Canada

Abstract

The proportionally high energy consumption and high Global horizontal irradiation (GHI) in Iran, are two primary motivations for this research to put into action on solar water pumping system for a garden in Iran. Storage systems are not used commonly since they add a high cost to solar water pumping systems. This academic work with emphasize on storage systems, aims to design an optimum solar water pumping system to not only decrease the cost of the system but also boost the availability of the system in order to convince farmers and gardeners to immigrate from conventional systems to a solar water pumping system. In this research, three solar water pumps with different storage system configurations are optimum sized using Homer pro for a site in Iran, and they are compared economically and technically. In addition, a new hybrid storage system consisting of both battery and water tank is proposed and it is optimized using imperialist competitive algorithms (ICA). It is shown that this hybrid storage system not only reduces the project cost, but also can take advantage of both battery and water thank benefits. Furthermore, a dynamic study is carried out with the help of simulations in MATLAB/Simulink. This simulation consists of Photovoltaic (PV) modules, Maximum Power Point Tracking (MPPT) unit and control center, inverter, storage system and water pump. The results of this study show that this new configuration for a solar water pump with a hybrid storage system is a better choice and economical than typical solar water pumps for irrigation.

Acknowledgment

First of all, I am thankful to God which I have felt her presence throughout the journey of my study.

I sincerely thank my supervisor, Dr. Tariq Iqbal who kindly guided and supported me with his great knowledge during my master’s program.

I Also, thank Roshana Gostar Shargh Barsava company that trust me and provided funding for my studies in master’s degree.

I would like to express my gratitude to Dr. Iman Ahadi Akhlaghi who shaped my academic personality and motivated me to pursue my post-graduate study.

The last but not least, I would like to thank my family who supported me with their unconditional love.

Table of Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

GHI	Global Horizontal Irradiation
ICA	Imperialist Competitive Algorithms
PV	Photovoltaic
CO2	Carbon Dioxide
°C	Degree Celsius
%	Percent
TDH	Total Dynamic Head
STC	Standard Testing Condition
MPPT	Maximum Power Point Tracking
CA$	Canadian Dollars
LCCA	Life-Cycle Cost Analysis
P&O	Perturbation and Observation
SCADA	Supervisory Control And Data Acquisition

Chapter 1: Introduction and Literature Review

1. Introduction

Iran is a country which uses a significant amount of energy and water yearly. This energy mainly comes from fusil fuels, while Iran can use alternative energy sources like solar energy. In this chapter, first, a background of water and energy consumption in Iran is given. Then it will touch upon an overview of the solar water pumping systems. Lastly, the motivation for this research and thesis organization is given.

1.1 Background of energy and water resources in Iran

Since Iran is one of the world's main oil and natural gas producers, the price of oil and natural gas is lower than in many other countries. This is why more than 80 percent of the electricity share belongs to fossil-fuel-based power plants (figure 1).

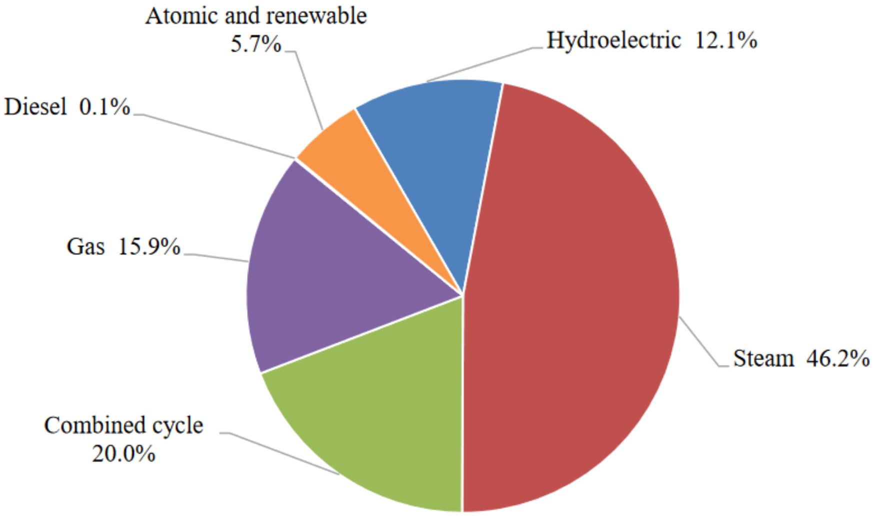


Figure 1: The share of electricity production in the years 2018-2019 [1]

In Iran, A significant share of the water resources is supplied by deep water wells (figure 2), which around 48.5 percent of total water consumption is for agricultural purposes [1]. Most farms and gardens are located in remote areas where it is necessary to produce electricity to provide power for their water pump. Traditionally, they use diesel generators that are not only environmentally friendly but also impose yearly maintenance costs on farmers and gardeners.

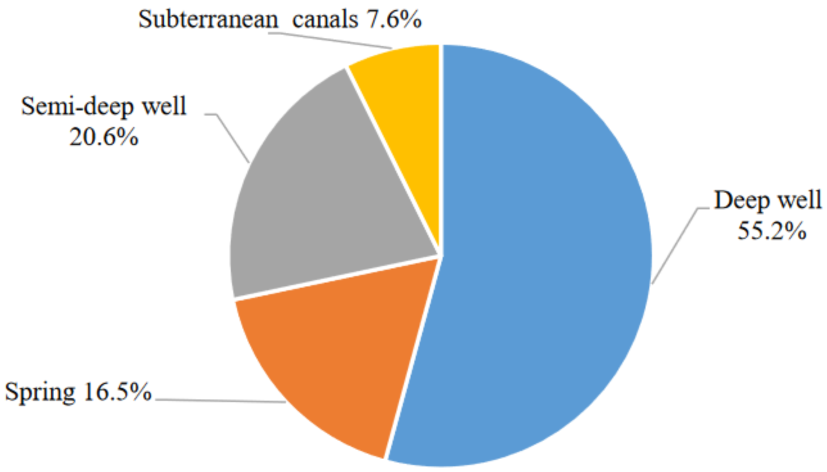


Figure 2: Percentage of water withdrawn from underground water resources in the years 2017-2019 [1]

Considering everything, it can be said that Iran is a country with a high energy and water consumption rate, which not only put pressure on its resources but also harms nature and the environment.

1.2 Solar water pumping systems and previous works

As is depicted in figure 3, a solar water pumping system consists of PV modules, converters and control units, storage, and water pump.

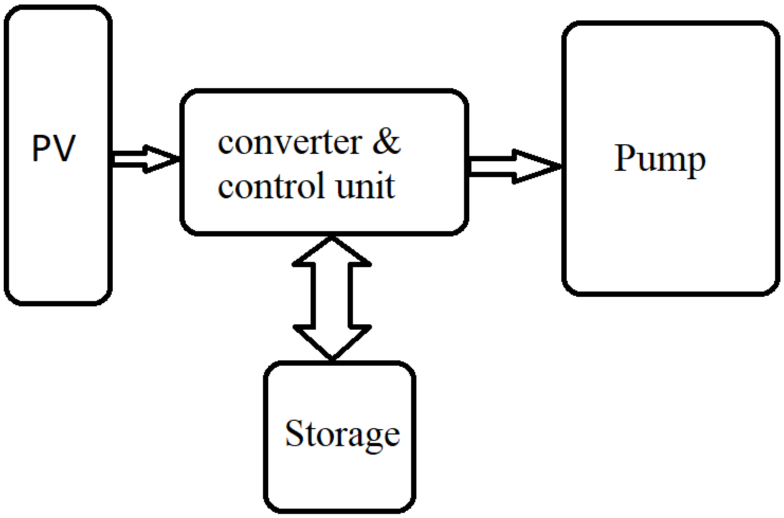


Figure 3: Main parts of a solar water pumping system

Previous works on solar water pumping systems can be categorized into three groups:

A: Stand-alone solar pumping systems without storage such as [2-4]. These researchers focused on designing a system consisting of only PV modules and water pumps connected directly or through an inverter.

B: Stand-alone solar pumping systems with a battery bank as storage like [5,6]. These researchers considered a battery bank as a back-up for solar water pump, which provides power for water pump when the sun is unavailable.

C: Stand-alone solar pumping systems with water tank as storage such as [7-10]. These researchers proposed a water tank as a back-up to store water directly in the tanks; whenever needed, it can be used for irrigation.

Some researchers focused on designing a solar water pumping system in Iran. Here are the most significant ones:

- *A financial comparative study of solar and regular irrigation pumps: Case studies in eastern and southern Iran*: In this research, they had an economical study of a solar water pumping system in two different areas. For a specific site they compared a solar water pump with a grid connected pump, they concluded that for a small-scale water pump (less than 4.5 KW) it is a better choice to use solar water pump and for larger water pumps it is more economical to used conventional water pumps [11].
- *Technical, economic, and environmental modeling of solar water pump for irrigation of rice in Mazandaran province in Iran: A case study*: In this research, in addition to economical analysis, they focused on economical aspects of solar water pumping systems. They showed that the initial cost for a solar water pump system with battery storage is about 2 times of diesel pumping systems, but operating and maintenance costs are approximately 8 times less that diesel pumping systems. Also, they claimed that solar pumping in comparation with diesel pumps reduce CO2 emissions about 17 times and reduce noise around 70% [12].
- *Development of an Economical SCADA System for Solar Water Pumping in Iran:* In this research, the authors design a low cost SCADA system for a solar water pumping system in Iran. They set-up a lab scale SCADA system based on sensors and Raspberry pi and communications modules. They implement this cost efficient and provide their results [13] .

1.2 Research objective and motivations

While there was a development in renewable generation like solar PV(figure 4), the shared renewable energy in total energy consumption has been approximately the same during the past decades (figure 5). This shows a need for more research and study in the realm of renewable energy systems in Iran.

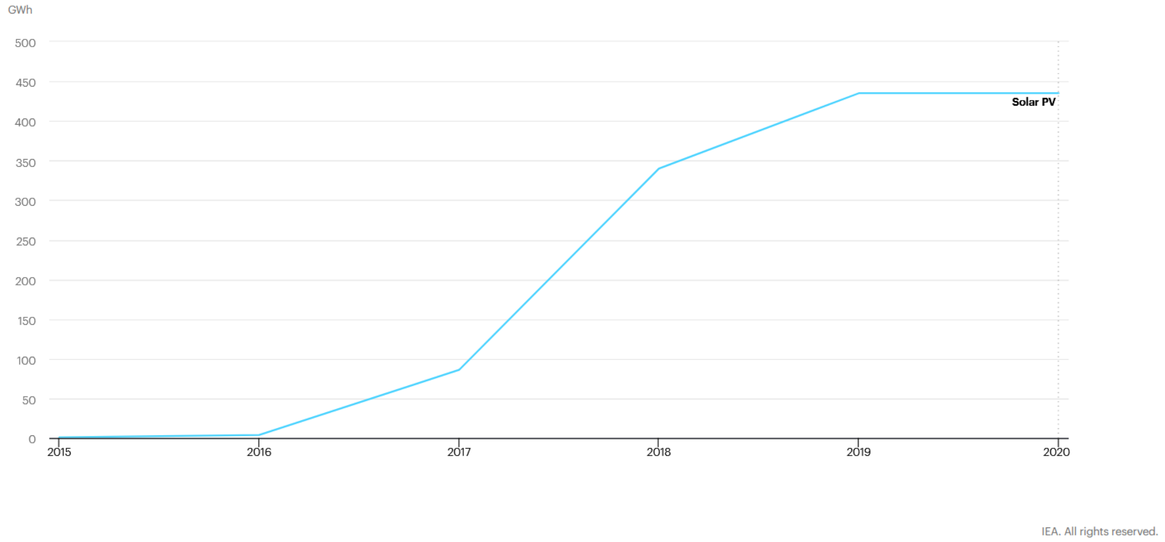


Figure 4: Solar PV electricity generation, Islamic Republic of Iran 2015-2020 [14]

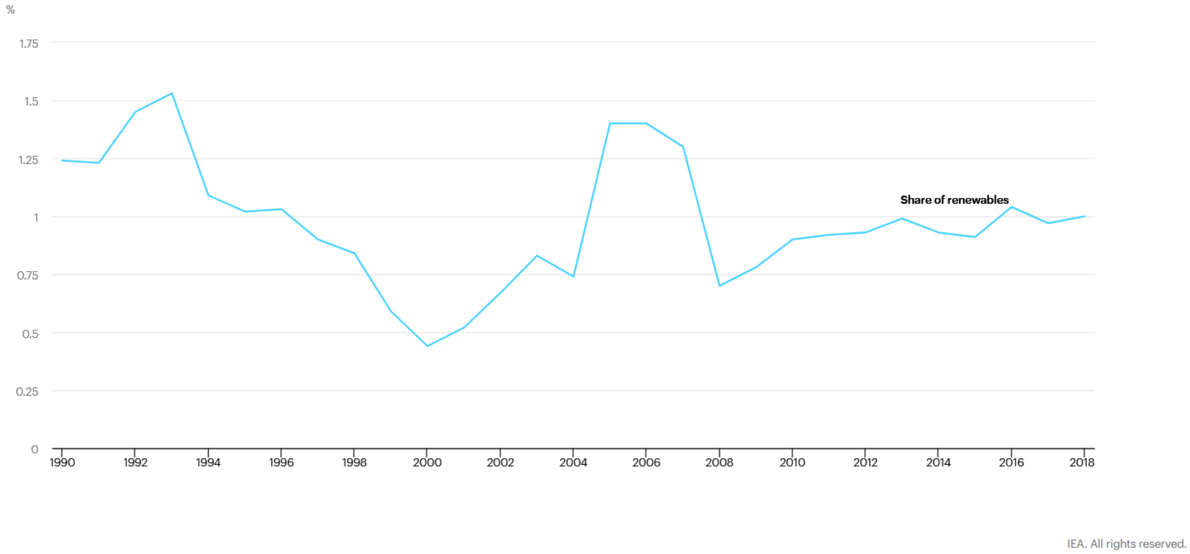


Figure 5: Renewable share in final energy consumption (SDG 7.2), Islamic Republic of Iran 1990-2018 [14]

Many studies have been done in the past couple of years, but since they are not cost-efficient, they are not feasible enough to employ for actual conditions. This study tries to conduct some research on optimization for a solar-energy-based system to propose a practical system with a reasonable price and acceptable reliability.

As mentioned, the main portion of water consumption in Iran is for irrigation in farms and gardens, and the water resource for this irrigation is mostly from deep and semi-deep water wells. Currently, diesel generators are widely used to provide power for water pumps which are not environmentally friendly.

These two reasons are the main motivation for this research to provide an optimum solar water pump for a specific site in Iran with actual data and environment conditions. The suggested system could be a possible configuration to substitute conventional water pump systems.

Thesis research objectives are:

- Site selection and system design with storage
- Optimization of hybrid storage of solar water pumping
- Dynamic modeling of solar pumping system with storage.

1.4 Thesis Organization

A manuscript-style format has been used to prepare this thesis. This thesis consists of 5 chapters which a brief summary of the following chapters is presented below:

Chapter 2: In this chapter, the first main steps for designing a solar water pumping system are expressed. After introducing site specifications, three solar water pumps with different storage system configurations are optimum sized using hand calculation and Homer pro software. In the end, there is a comparison between these three storage system configurations.

Chapter 3: This chapter presents a new hybrid configuration for storage system in solar water pumping systems. In order to reach an optimum design, first, the optimization problem is clearly defined, and the approach to solving this problem is presented. It is concluded that a solar water pumping system with a hybrid storage system is a better and economical solution.

Chapter 4: In this chapter, the dynamic model of all principal parts of the proposed system is provided, and a simulation based on these models is done with the help of MATLAB/Simulink. In the end, the results of this dynamic study are presented.

Chapter 5: This chapter provides a review of this research's major gains and suggested future work.

References:

[1] “The Statistical Centre of Iran, 2019. Iran Statistical Yearbook 1397 (2018 – 2019).” https://www.amar.org.ir/english/Iran-Statistical-Yearbook/Statistical-Yearbook-2018-2019 (accessed Dec. 28, 2021).

[2] Bangari, Naresh & Madhu, P & Prasad, K & Prof, Asst. (2012). Analysis Of Dc Solar Water Pump and Generalized Photovoltaic Model Using Matlab/Simulink. UACEE International Journal of Advancements in Electronics and Electrical Engineering Volume 1: Issue 1. 1. 6.

[3] Mahmoud M. Elkholy, Ahmed Fathy, Optimization of a PV fed water pumping system without storage based on teaching-learning-based optimization algorithm and artificial neural network, Solar Energy, Volume 139, 2016, Pages 199-212, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2016.09.022.

[4] A. Betka, A. Attali, Optimization of a photovoltaic pumping system based on the optimal control theory, Solar Energy, Volume 84, Issue 7, 2010, Pages 1273-1283, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2010.04.004.

[5] M. Zamanlou and M. T. Iqbal, "Design and Analysis of Solar Water Pumping with Storage for Irrigation in Iran," 2020 IEEE 17th International Conference on Smart Communities: Improving Quality of Life Using ICT, IoT and AI (HONET), 2020, pp. 118-124, doi: 10.1109/HONET50430.2020.9322660.

[6] F. Alkarrami, T. Iqbal and K. Pope, "Optimal sizing of a stand-alone hybrid energy system for water pumping in Sirte, Libya," 2016 IEEE Electrical Power and Energy Conference (EPEC), 2016, pp. 1-5, doi: 10.1109/EPEC.2016.7771679.

[7] Kiprono, A. W., & Llario, A. I. (2020). Solar Pumping for Water Supply: Harnessing solar power in humanitarian and development. pp 68-69

[8] Yahia Bakelli, Amar Hadj Arab, Boubekeur Azoui, Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept, Solar Energy, Volume 85, Issue 2, 2011, Pages 288-294, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2010.11.023.

[9] Soenen, Camille & Reinbold, Vincent & Meunier, Simon & Cherni, Judith & Darga, Arouna & Dessante, Philippe & Loic, Queval. (2021). Comparison of Tank and Battery Storages for Photovoltaic Water Pumping. Energies. 14. 2483. 10.3390/en14092483.

[10] Wagdy R. Anis, M.A. Nour, Optimum design of a photovoltaic powered pumping system, Energy Conversion and Management, Volume 35, Issue 12, 1994, Pages 1123-1130, ISSN 0196-8904, https://doi.org/10.1016/0196-8904(94)90016-7.

[11] Rizi, A. P., Ashrafzadeh, A., & Ramezani, A. (2019). A financial comparative study of solar and regular irrigation pumps: Case studies in eastern and southern Iran. Renewable Energy, 138, 1096-1103.

[12] Nikzad, Amirhossein, Mahmood Chahartaghi, and Mohammad Hossein Ahmadi. "Technical, economic, and environmental modeling of solar water pump for irrigation of

rice in Mazandaran province in Iran: A case study." Journal of Cleaner Production 239 (2019): 118007.

[13] M. Zamanlou and M. T. Iqbal, "Development of an Economical SCADA System for Solar Water Pumping in Iran," 2020 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), 2020, pp. 1-4, doi: 10.1109/IEMTRONICS51293.2020.9216408

[14] "Iran - Countries & Regions - IEA." https://www.iea.org/countries/iran (accessed Oct. 22, 2022).

Chapter 2: A Comparative Study of Solar Water Pump Storage Systems

A version of this manuscript has been peer-reviewed, accepted, and presented in 2022 IEEE 12th Annual Computing and Communication Workshop and Conference. The paper has also been published on IEEE Xplore Database as a part of 2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC) (doi: 10.1109/CCWC54503.2022.9720912.). I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired, provided the research guide, reviewed and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

2.1 Abstract

Solar water pumps are the best alternative for traditional pumping systems in countries with high solar irradiation especially middle east countries which face water shortage challenges and have many remote areas. The reliability of solar-based systems relies on energy storage elements which impose a high cost to project expenses. This issue discourages gardeners and farmers from replacing their existing system with a new solar

irrigation system. This research aims to size a cost-efficient solar water pump focusing on typical storage configurations to make the solar projects more practical and affordable for gardeners. In this paper, three solar water pump systems (without storage, battery storage, and water tank storage) are sized, and their advantages and disadvantages are discussed.

2.2 Introduction

When for the first time, Edmond Becquerel (French physicist) observed the photovoltaic effect in 1839, no one thought that one day this technology would be used as a primary source of energy in space projects [1]. During the last decade, solar cells have been used widely, from small-scales like solar power banks to mega scales like Bhadla Solar Park, the largest solar power plant globally [2].

In terms of economy and technical, besides knowing the advantages of solar-based systems, they have a notable drawback which is the need for a storage system; due to changes in solar irradiation during the 24 hours of a day, an energy storage system is vital to ensure the stability and reliability of the system. Storage systems, usually battery banks, impose a high cost on solar-based systems; thus, the optimum design of a storage system could save money on investments and help the system operate more efficiently.

There are two typical storage systems for solar water pumping systems powered by Photo Voltaic (PV) panels 1- battery banks 2- water tanks. Both systems have their advantages and disadvantages, which will be discussed later on. This research aims to design an optimum size for a solar water pump with storage system consisting of batteries or water tanks for a site in Iran to reduce the project expenses and increase the system efficiency.

First, a background of electricity water consumption will be given in this paper; then, an overview of storage systems in solar water irradiation and related previous work will be discussed. The proposed systems sizing for a specific location in Iran are provided in part 4 and they are discussed in section 5. In the end, a conclusion of the results of the proposed systems will be given.

2.3 Iran Electricity and Water Consumption

During the past four decades, Iran has experienced a surge in population from 28.5 million people in the year 1970, raised to 84 million people in 2020; as a result, water withdrawals and electricity consumption increased more than expected [3]. Here are some statistics of Iran's electricity and water consumption trends in recent years.

2.3.1 Electric energy consumption in Iran

Energy consumption in Iran is among the first 10 top countries in the world. This energy is mainly used for electricity and heat production purposes; since oil and natural gas are the primary sources of energy in Iran, this trend has resulted in high CO2 (carbon dioxide) emissions (figure 6) [4].

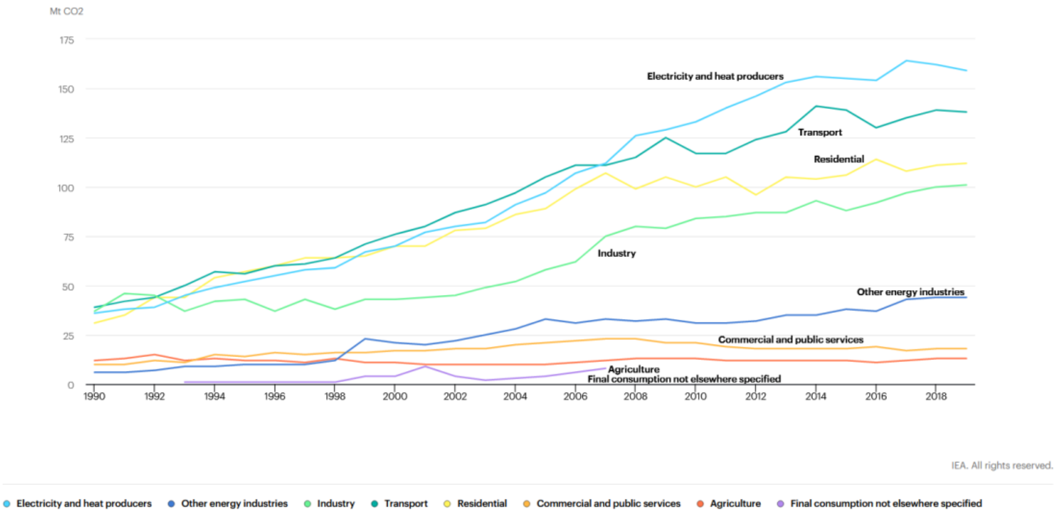


Figure 6: CO2 emissions by sector, Islamic Republic of Iran 1990-2019 [4]

In recent years, due to air pollution challenges in many cities in Iran, the government has encouraged people to use renewable energy sources, especially photovoltaic (PV), for their electricity demands; this encouragement policy for the major project includes long term loans and for a household is guaranteed to buy exceed produced electricity in a reasonable price. This policy results in a slight increase in solar PV electricity generation after the year 2016 [4]. However, because of the increase in electricity demand in recent years, the renewable share in final energy consumption remains almost the same [4].

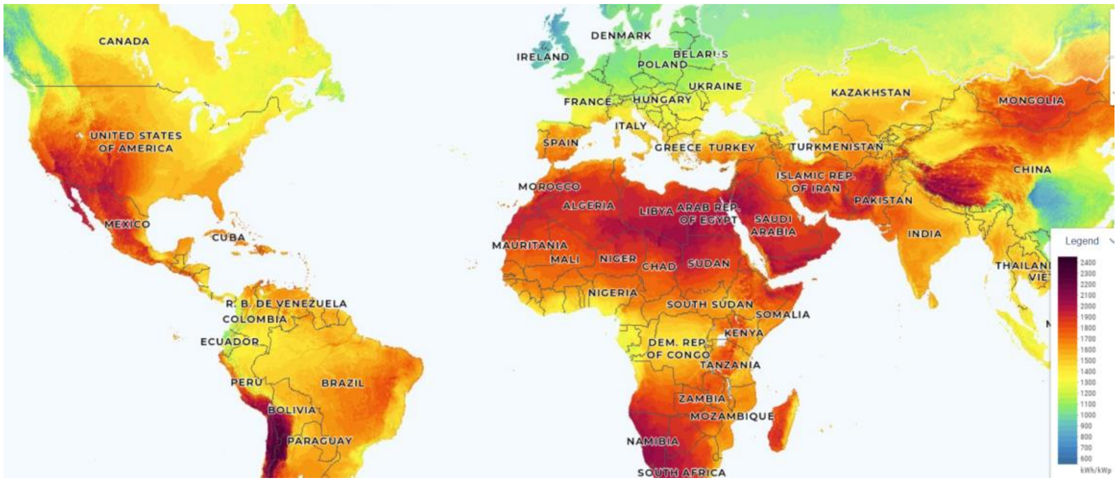


Figure 7: Global horizontal irradiation [5]

Iran's GHI (Global horizontal irradiation) is between 4.04 and 6.95 KWh/m2, making Iran an ideal PV production location (illustrated in figure 7) [5]. However, unfortunately, as shown in figure 8, the share of PV is a minor source of electricity (less than 5 percent) [5], [6]. This trend shows a need for more study and investment in the industrial, household, and agricultural systems to boost the share of solar PV in electricity production. Figure 7 clearly shows that Iran is among countries with high potential for PV installations.

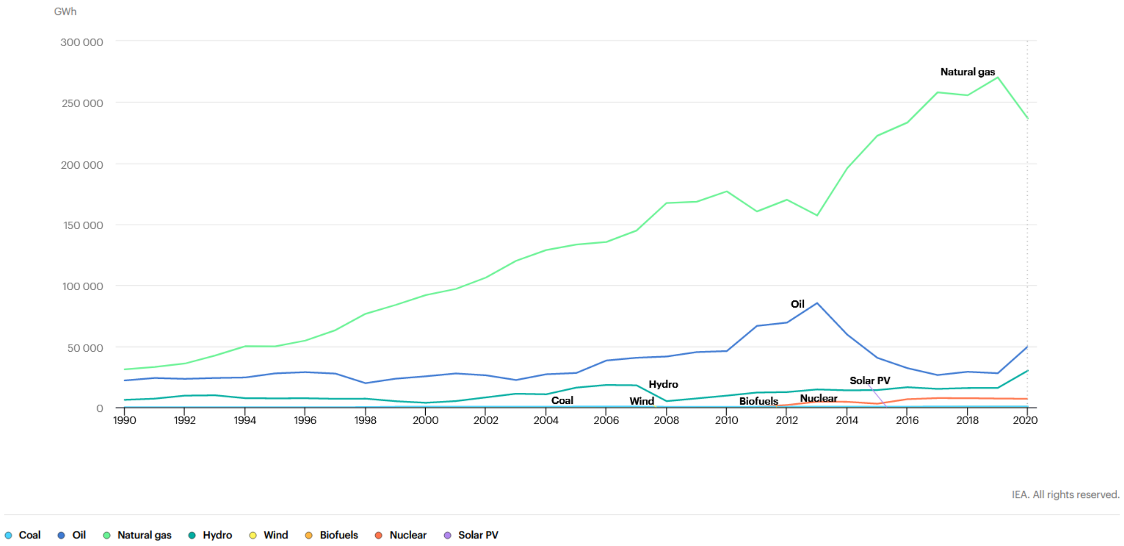


Figure 8: Electricity generation by source, Iran 1990-2020 [4]

2.3.2 Water consumption in Iran

Global warming and water scarcity are worldwide challenges, but this shortage is more significant for Middle Eastern countries like Iran. Figure 9 shows the world's water stress, which is defined as “ the ratio of total water withdrawals to available renewable surface and groundwater supplies” [7].

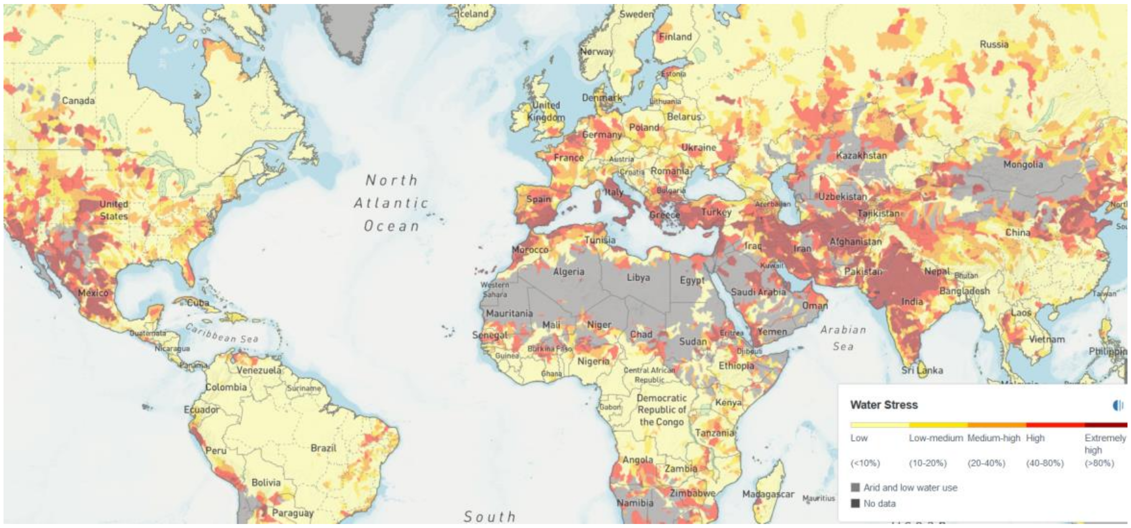


Figure 9: Water Stress in world [7]

Based on the statistical center of Iran, ironically, about 48.5 percent of water is consumed for agricultural purposes, which is a significant share of water consumption; in addition, since most power plants in Iran are thermal, they use water which itself results in more drought in Iran [6].

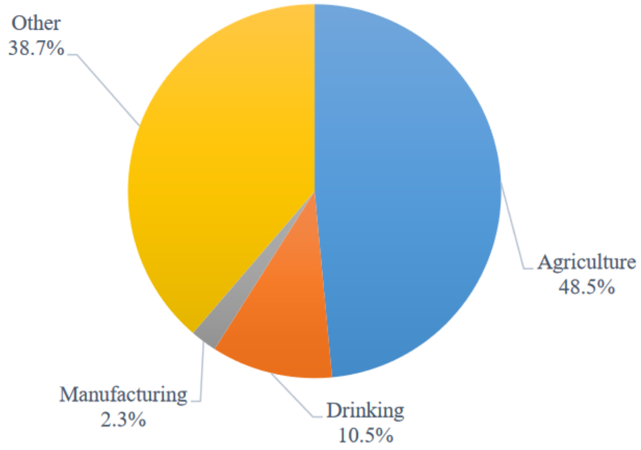


Figure 10: water consumption by type of use in Iran, the years 2018-2019 [6]

According to what is said, a PV-based irrigation system saves energy and decreases water consumption in power plants. Based on the statistics of Iran's statistical center, about 55 percent of needed water is supplied by deep wells and 20.6 percent by semi-deep wells; thus, designing solar water pumping for deep or semi-deep wells is significant [6].

2.4 Optimum Solar Water Pumping Storage

Storage in solar irrigation systems can be divided into three groups 1- without storage 2- battery bank storage 3- water tank storage; in the following sections, each group is discussed, and related previous work is referenced.

2.4.1 Solar water pumping without storage

Rapidly changes in solar irradiation (input power) is the nature of solar energy based systems, because first of all, the sun is just available during the day time and also it is vary from sunrise to sunset; due to this reason, a storage system is necessary for such systems to provide reliability and work smoothly.

To decrease the expenses in solar pumping systems, some designers directly connect the PV arrays to a DC pump to irrigate the farm. Here are two main problems:

1. In a case of a cloudy day, the system doesn’t work, and if it continues for a couple of days in a row, it might harm the crops.

2. Input power to PV arrays should reach a specific lever to start the DC pump, and in the afternoon, when solar irradiation drops less than a specific level, the DC pump will be off; as a result, the system misses an amount of power in the early morning and late

afternoon. For example, figure 7 illustrates I-V curves for PV; the DC pump start running when enough output is available.

Some designs focused on stand-alone solar pumping systems without storage like [8]–[10].

2.4.2 Solar water pumping with battery back-up

The most popular back-up system for renewable energy based systems are battery banks; it is a reliable back-up system that stores electrical energy in their electrochemical cells. It is very straightforward to calculate the minimum needed batteries for the intended design system; also, there are some software available for designing optimal PV-based systems like Homer Pro, iHOGA, etc., which determine the optimum battery back-up capacity of a stand-alone system. Many papers proposed their optimum system using Homer Pro or IHOGA [11], [12].

2.4.3 Solar water pumping with water tanks

Some resources recommend avoiding using batteries as a back-up system due to power loss, yearly inspection and maintenance, short life span, which imposes replacement cost and disposal challenges after the end of the lifespan; instead, they proposed water tanks for irrigation systems that directly store water in reservoirs [13]. Some works design an optimum solar pumping system with water tanks like [14]–[16].

2.5 Optimize Sizing of Solar Water Pumping for Irrigation in Iran

In order to reach an optimum size of a solar irrigation system, three main steps should be taken; first, it is necessary to collect vital specifications of the undertaken site and then choose proper system components according to availability in the local market and technical compatibility. In the end, do calculations and simulations based on acquired information. In this part, these three steps are explained in detail.

2.5.1 Site specifications

One of the necessities of practical solar pumping projects is collecting and studying the intended site. More updated data with more detail will result in more accurate calculation and simulation, which leads to fast and efficient progress on the day of project implementation. These data consist of site location and covered area, ambient conditions statistics, especially solar GHI and temperature, current under operation system specifications like water well and pump power source, and the minimum needed daily water for irrigating the trees or crops. This section touch upon these collected data for a site in Iran.

2.5.1.1 Location: For this research, a site (see figure 11) is considered at 30 km from Mashhad, Iran. The total area of this site is approximately 220000 m2 which has many apple and cherry gardens. This area comprises about 20 smaller gardens with shared water well.

2.5.1.2 Solar irradiation and ambient temperature: Solar irradiation and ambient temperature are two main factors in designing a PV-based system [17]; figure 12 shows that an increase in cell temperature results in a decrease in open-circuit voltage, and reduce in solar irradiation results in a drop in short-circuit current.

Figure 11: Satellite image of the site location (Source: Google earth)

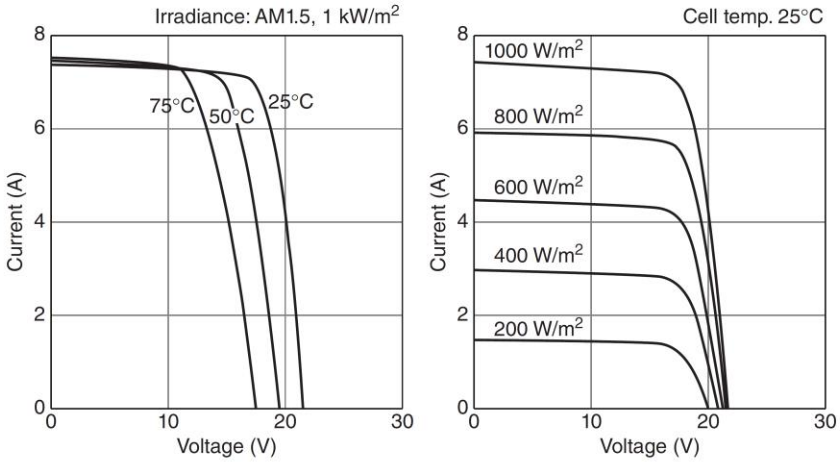


Figure 12: I-V curve of a PV module in different temperature and irradiation [17]

Figures 13 and 14 illustrate that the highest irradiation and temperature is between April to September, resulting in high demand for irrigation; thus, the solar water pump should be designed efficiently to satisfy needed water during these months.

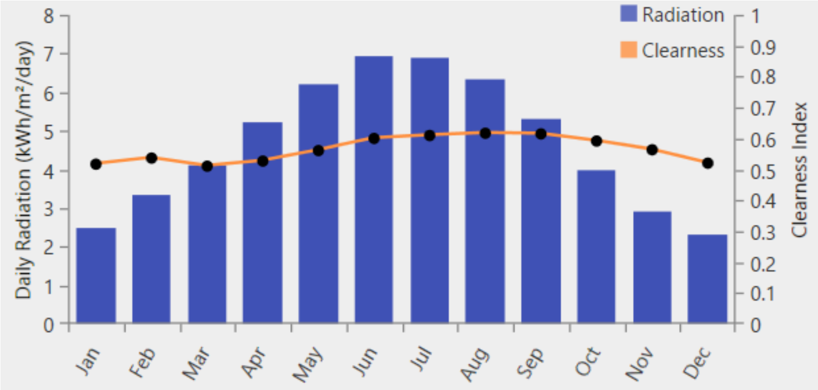


Figure 13: Mean daily radiation and clearness index of the site (Source: Homer)

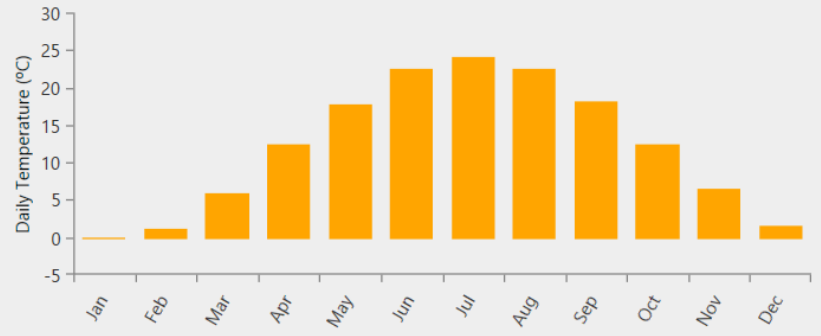


Figure 14: Mean daily temperature of the site (Source: Homer)

2.5.1.3 Current running system: At present, the needed water is supplied by semi-deep water well with a submersible water pump powered by a diesel generator. In the past, surface irrigation was used, but during the decade with severe drought, gardeners have been replacing surface irrigation with drip irrigation; currently, more than 50 percent of the irrigation system is drip irrigation. In the following detailed systems are explained.

- *well and total dynamic head:* TDH (Total dynamic head) is the equivalent height which water should be pumped; it is calculated as follows [13]:

$$TDH = H_D + H_V + H_F + H_R$$

where:

H_D = the height from dynamic water level to borehole surface

H_V = the height from borehole surface to tank inlet

H_F = the fraction lost because of pressure drop in piping

H_R = residual head, which is the additional height from tank inlet to delivery point

The figure 15 illustrates the calculated TDH for the understudy water well; according to those calculations, the TDH for this site is 167 meters that for a better result, 170 meters is considered

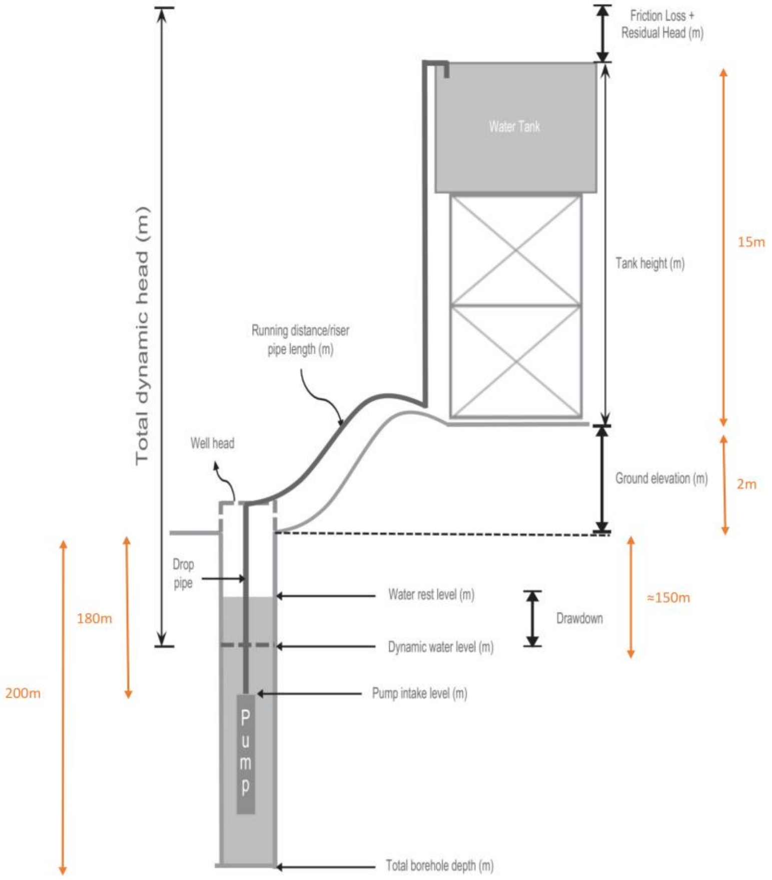


Figure 15: TDH calculation (adopted and modified from [13])

- *Generators:* This site uses two diesel generators with 44 KVA nominal power as primary and auxiliary. Gasoline is stored in two fuel tanks which are refilled regularly by a fuel truck (see figure 16 and 17). This system has been operated for more than 20 years; as it is getting nearer to its expected life span, the maintenance cost has an increasing trend and notable system interruptions. Also, there might be some environmental hazards due to fuel overflow at the time of fuel refilling and fuel tank leakage; because of these matters, gardeners desire to replace this system with a cleaner and reliable system. This research aims to design a cost-efficient system for this site to encourage gardeners to replace this system with a solar water pump system.

Figure 16: Current operating generators


Figure 17: Fuel tanks

- *water demand profile*: based on a local survey, gardeners need 6 m^3 of water per 1000 m^2 of the field; also, every day, just a part of these gardens is watered, and the water cycle turns every seven-day. As a result:

water which is needed for every seven days:

$220 \times 6 = 1320\ m^3$

minimum needed water for irrigating for one day: $1320 \div 7 = 188.6\ m^3/day$

If the pump works 7 hours a day, the flow rate is:

Flow rate = $188.6 \div 7 \cong 27\ m^3/hour$

2.5.2 Selecting solar water pumping system components

Selection in this research was based on two criteria, availability in the local market and technical satisfaction. The selected system components are listed below:

2.5.2.1 Pump: Lorentz is one of the pioneers of solar water pumping. This company provide a wide range of water pump. According to the minimum needed water flow (27 m^3/hour) and TDH (170 m), the company recommends *Lorentz PSK2-40*; this is a submersible water pump with characteristic curves which is shown in figure 18; this figure illustrates that for a well with 170 m of TDH and 27 m^3/hour of needed water flow, the pump needs about 22 KW power.

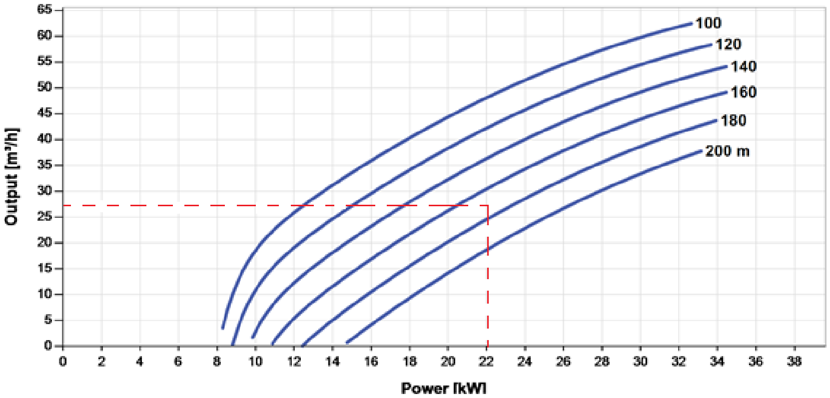


Figure 18: Lorentz PSK2-40 curves (source: Lorentz handbook)

2.5.2.2 PV panels: JC-340-72P is considered for this research. This is a Poly PV module with 340 W maximum power in Standard Testing Condition (STC); the module dimension is 1.002×1.979 meter.

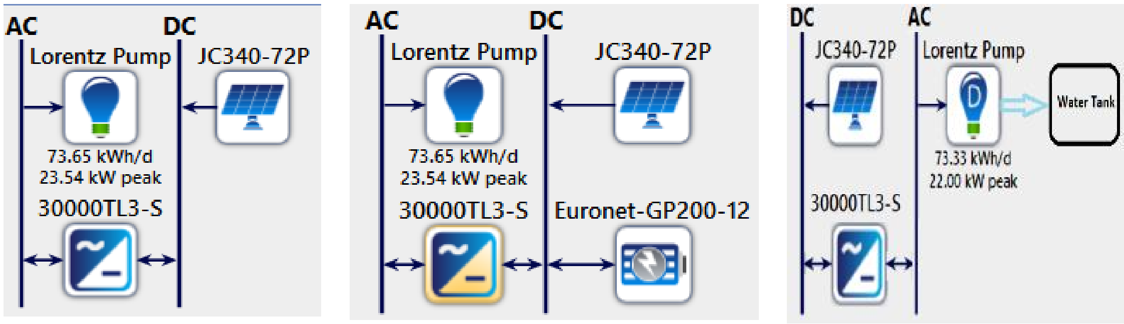
2.5.2.3 Batteries: GP200-12 is a 200Ahr Gel battery widely used for solar-based systems as a reliable energy back-up system.

2.5.2.4 Inverter: Growatt 33000TL3-S is an MPPT solar inverter with 33 KVA apparent power and 30 KW rated power.

2.5.2.5 Water reservoir: For water tank “galvanized steel water tank tower” is considered which they are typically used in Iran because 1: easy to build and install 2: long last lifespan 3: cheaper than polyethylene or concrete tanks.

2.5.3 Optimum solar pumping

So far, the minimum required information for a solar water pump is given; in this section, the calculations and system sizing based on three typical storage configurations will be done. Figure 19 shows three configurations of possible designs for the site.



a b c

Figure 19: different storage configuration: a) without storage b) battery storage c) water tank storage

2.5.3.1 optimum solar pumping without storage: a system without storage is the simplest configuration which is used to reduce the project expenses due to the high initial cost of storage systems. These systems are unreliable and have fluctuation in output water, which relies on solar irridiation. The sizing of these systems are quite straightforward and can be done like follow:

Panel area = $1.002 \times 1.979 = 1.98\ m^2$

Max power (STC) = 340 W

Irradiance (STC) = $1000\ W/m^2$

Panel efficiency = $340 / (1000 \times 1.98) \times 100 = 17.17\%$

Solar irradiation in the site location is 4.67 KWh/m^2 per day

So we need 7×22KWh = 154 KWh/day

Arraysize=(154KWh⁄day)/(4.67KWh⁄(m^2.day)×0.1717×0.7)= 274.37m^2

Number of modules= ⌈(274.37m^2)/(1.98 m^2)⌉=139

Power of each modules is 0.34 KW, so:

Total power = 139×0.34 = 47.26 KW

The cost of each module in Iran is about 150 CA$, so the cost for PV panels will be:

139 × 150 = 20,850 CA$

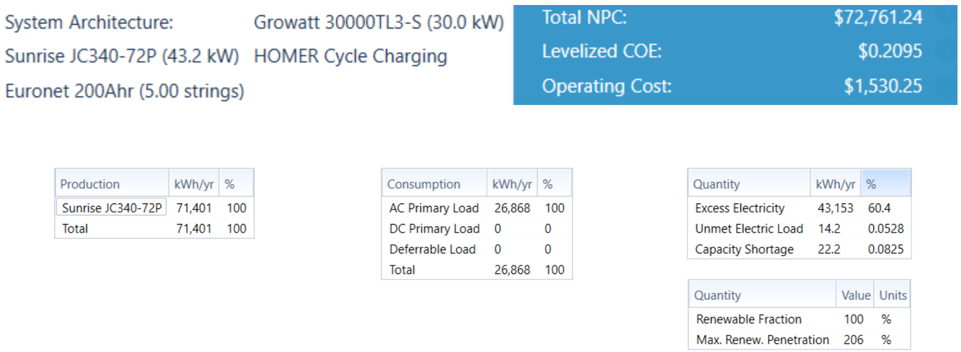
The price of the inverter is about 3000 CA$ in Iran, which should be replaced after 10 years; thus, to cost the inverter for project lifetime (25 years) is:

3000 × 3= 9000 CA$

As a result, the total cost of the project is:

20,850 + 9000 ≈ 30,000 CA$

2.5.3.2 optimum solar pumping with battery storage: This is the most typical configuration for solar water pumping. The sizing can be done using Homer Pro; This software computes the most optimum quantity of elements based on location and selected components. Figure 20 shows Homer Pro system sizing result, suggesting using 43.2 KW solar panel, five strings of 20 batteries (100 batteries in total), and a Growatt 30000TL3-S inverter.



System Architecture: Growatt 30000TL3-S (30.0 kW)
Sunrise JC340-72P (43.2 kW) HOMER Cycle Charging
Euronet 200Ahr (5.00 strings)

Total NPC: $72,761.24
Levelized COE: $0.2095
Operating Cost: $1,530.25

Production	kWh/yr	%
Sunrise JC340-72P	71,401	100
Total	71,401	100

Consumption	kWh/yr	%
AC Primary Load	26,868	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	26,868	100

Quantity	kWh/yr	%
Excess Electricity	43,153	60.4
Unmet Electric Load	14.2	0.0528
Capacity Shortage	22.2	0.0825

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	206	%

Figure 20: Homer Pro analysis results

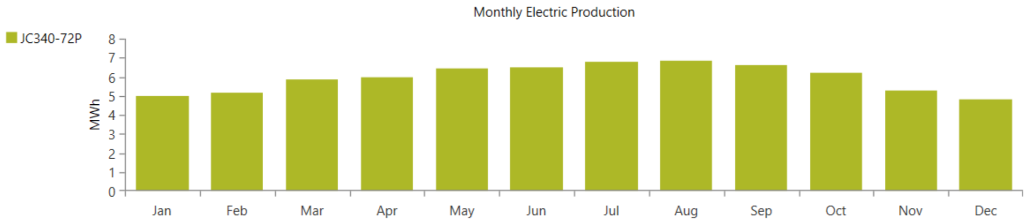


Figure 21: Electrical power flow

Figure 21 depicts that most electricity production is during the summertime, which perfectly matches the load demand during the same period of time.

2.5.3.3 optimum solar pumping with water tank storage: sizing this configuration is a bit challenging because this system consists of electrical elements and a water tank. Usman Ashraf has proposed a technique to size an optimum design for a solar pump with a water tank [18]; the following calculations are based on this technique:

As mentioned, the minimum needed water for irrigating for one day in this site is about 188.6 m^3/day, so a tank with 188 m^3 is needed. It takes about 7 hours to fill this tank with the water pump at 22KW power; as a result, 22KW × 7 = 154 KWh is storage capacity required. In this case, the water pump will be defined as a deferable load with 154 KWh storage capacity in Homer Pro.

Homer proposed at least 53.2 KW PV panel and a 30KW inverter for the electric part of the system. Based on Homer cost analysis, the total project cost is about 40,000 CA$, which should be added to the price of the water tank. A 200 m^3 water tank (four number of 50 m^3 water tanks in series) in Iran is about 16,000 CA$; thus, the total project cost will be approximately 56,000 CA$.

2.6 Discussion

In the previous sections, three different configurations for solar water pumping in Iran are proposed; the summary of the results is mentioned in table 1:

Table 1: Compare different storage configurations

Configuration	Cost (CA$)	Advantages	Disadvantages
Without storage	30,000	Low cost	Unreliable
Battery storage	72,800	Provide a constant power to pump, which results in a higher life span of the pump	Replacement and maintenance cost
Water tank storage	56,000	High life-span	Difficulty in build and installation of high-capacity water tanks

Due to high risk, the first design is not proper for use in this site. Both second and third design has their advantages and disadvantages that cannot be said which one has superiority over another one; but the table above shows that for a system with storage, water tank will have a lower cost. Therefore, such a system is recommended for the selected site.

2.7 Conclusion

In this paper, three solar water pumps systems based on their storage configurations are considered for a rural area in Iran, and their benefits and drawbacks are discussed. Among these configurations, a system with water tank storage is recommended for under studied area because not only it guaranteed reliability of the system, but also provide a storage system at a reasonable price.

This system is consist of a Lorentz PSK2-40 submersible water pump which is proper for calculated TDH, 157 modules of JC-340-72P PV panel with 340 W output power, a Growatt 33000TL3-S inverter with 30 KW rated power, and 200 m^3 water tank to meet the minimum needed water back up for a day.

More works could be done for different rural or remote areas, especially in Iran and compare site sensitivity and resources in order to decide on a proper storage configuration for the system.

2.8 Acknowledgment

The authors kindly thank Roshana Gostar Shargh Barsava for providing funding for this research.

References

[1] R. Williams, “Becquerel photovoltaic effect in binary compounds,” J. Chem. Phys., vol. 32, no. 5, pp. 1505–1514, 1960.

[2] “With 2,245 MW of Commissioned Solar Projects, World’s Largest Solar Park is Now at Bhadla - Mercom India.” https://mercomindia.com/world-largest-solar-park-bhadla/ (accessed Dec. 28, 2021).

[3] “Population, total - Iran, Islamic Rep. | Data.” https://data.worldbank.org/indicator/SP.POP.TOTL?locations=IR (accessed Dec. 28, 2021).

[4] “Iran - Countries & Regions - IEA.” https://www.iea.org/countries/iran (accessed Dec. 28, 2021).

[5] “Global Solar Atlas.” https://globalsolaratlas.info/map?c=32.713355,53.701172,5&r=IRN (accessed Dec. 28, 2021).

[6] “Statistical Center of Iran > Iran Statistical Yearbook > Statistical-Yearbook-2018-2019.” https://www.amar.org.ir/english/Iran-Statistical-Yearbook/Statistical-Yearbook-2018-2019 (accessed Dec. 28, 2021).

[7] “Aqueduct Water Risk Atlas.” https://www.wri.org/applications/aqueduct/water-risk-

atlas/#/?advanced=false&basemap=hydro&indicator=bws_cat&lat=24.766784522874453 &lng=-3.6914062500000004&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scenario=optimistic&scope=baseline&timeScale=annual&year=baseline&zoom=3 (accessed Dec. 28, 2021).

[8] B. Naresh, P. Madhu, and K. R. K. Prasad, "Analysis of DC solar water pump and generalized photovoltaic model using Matlab/Simulink," UACEE Int. J. Adv. Electron. Electr. Eng., vol. 1, no. 1, 2011.

[9] M. M. Elkholy and A. Fathy, "Optimization of a PV fed water pumping system without storage based on teaching-learning-based optimization algorithm and artificial neural network," Sol. Energy, vol. 139, pp. 199–212, 2016.

[10] A. Betka and A. Attali, "Optimization of a photovoltaic pumping system based on the optimal control theory," Sol. Energy, vol. 84, no. 7, pp. 1273–1283, 2010.

[11] M. Zamanlou and M. T. Iqbal, "Design and Analysis of Solar Water Pumping with Storage for Irrigation in Iran," in 2020 IEEE 17th International Conference on Smart Communities: Improving Quality of Life Using ICT, IoT and AI (HONET), 2020, pp. 118–124.

[12] F. Alkarrami, T. Iqbal, and K. Pope, "Optimal sizing of a stand-alone hybrid energy system for water pumping in Sirte, Libya," in 2016 IEEE Electrical Power and Energy Conference (EPEC), 2016, pp. 1–5.

[13] A. W. Kiprono and A. I. Llario, “Solar Pumping for Water Supply: Harnessing solar power in humanitarian and development.” Rugby, UK: Practical Action Publishing, 2020.

[14] Y. Bakelli, A. H. Arab, and B. Azoui, “Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept,” Sol. energy, vol. 85, no. 2, pp. 288–294, 2011.

[15] C. Soenen et al., “Comparison of Tank and Battery Storages for Photovoltaic Water Pumping,” Energies, vol. 14, no. 9, p. 2483, 2021.

[16] W. R. Anis and M. A. Nour, “Optimum design of a photovoltaic powered pumping system,” Energy Convers. Manag., vol. 35, no. 12, pp. 1123–1130, 1994.

[17] G. M. Masters, Renewable and efficient electric power systems. John Wiley & Sons, 2013.

[18] U. Ashraf and M. T. Iqbal, “Optimised Design and Analysis of Solar Water Pumping Systems for Pakistani Conditions,” Energy Power Eng., vol. 12, no. 10, p. 521, 2020.

Chapter 3: An Optimum Sizing for a Hybrid Storage System in Solar Water Pumping Using ICA

A version of this manuscript has been peer-reviewed, accepted, and presented in 2022 IEEE International IOT, Electronics and Mechatronics Conference. The paper has also been published on IEEE Xplore Database as a part of 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS) (doi: 10.1109/IEMTRONICS55184.2022.9795848.). I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired, provided the research guide, reviewed and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

3.1 Abstract

Solar water pumps must be the most optimum size to work efficiently and be at a reasonable price. The storage system can play a main role in both system reliability and the total cost of a solar water pumping project; thus, it should be designed carefully. Traditionally, only batteries or water tanks are used as primary storage system; each of them has its benefits

and drawbacks. In this research, a new approach to a storage system is proposed, consisting of both batteries and water tanks at the same time. Such hybrid storage can decrease project cost and increase system reliability. To find the most optimum size for such a hybrid system an optimization algorithm named “Imperialist Competitive Algorithm (ICA)” is used to minimize the Life-Cycle Cost Analysis (LCCA) of the storage system. In this paper, a hybrid storage configuration for solar water pumping for a site in Iran is proposed, and results of the optimum size for that system using ICA are expressed. It is shown that the configuration is more feasible compared with many other configurations.

3.2 Introduction

These days, conventional pumping systems are replaced with solar water pumping in remote areas, especially in Middle East countries. The most significant issue with solar-based systems, including solar water pumping, is storage systems, which increase solar projects' cost [1].

In the authors' previous work [1], two configurations of storage systems, battery storage and water tank, were proposed, and the advantages and disadvantages of each system were discussed. It is wise to design a hybrid storage system consisting of batteries and water tanks to take advantage of both systems. In addition, the system's reliability will be increased because in case of failure in either water tank or battery bank, another one can cover partial needed storage.

Apart from what is said, the most motivation to have a hybrid storage system is that if only batteries are used as a storage system, it will be pricy, or if only a water tank is used as a storage system, an amount of produced solar energy will be missed because PV output should reach to a specific power to run the pump in the morning, and when the output power drops below a threshold point, the pump will be stopped. So, the produced power in the early morning and late afternoon will be missed as shown in figure 22 below.

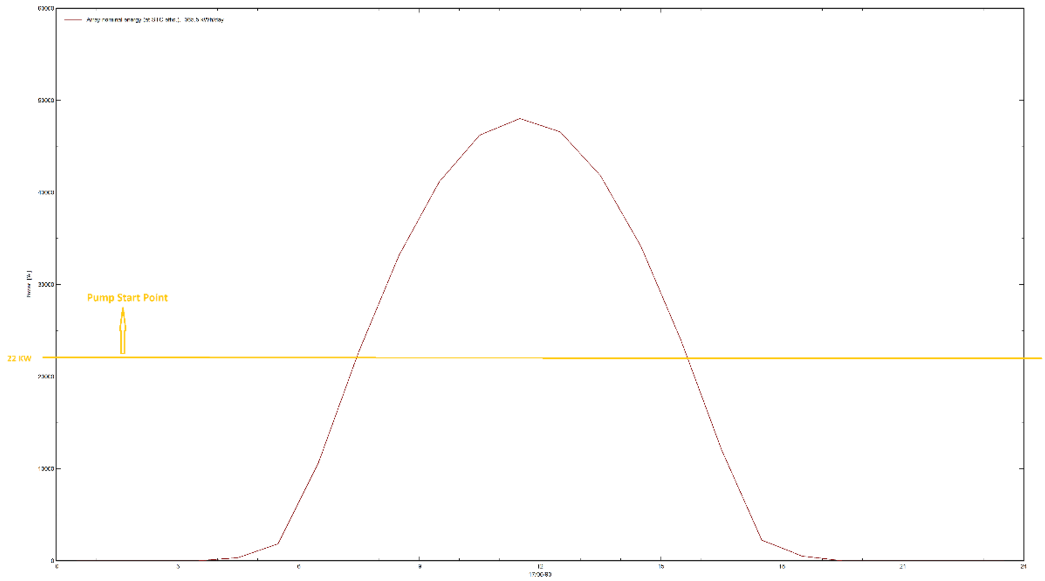


Figure 22: Nominal output array power for the site in Iran (for June 17th)

Since a hybrid system consists of both battery and water tank, conventional design software like Homer pro or PVSYS cannot be employed. Thus, an optimization method should be employed to calculate the optimum size of battery storage or water tank storage system in this hybrid system. Due to complications of this optimization problem and storage constraints, the "Imperialist Competitive Algorithm (ICA)" is used; this evolutionary algorithm is more efficient and straightforward to implement in comparison with typical optimization methods.

In this paper, first, an overview of hybrid storage systems is given; then, the optimization problem is defined in detail. After expressing the ICA, it is shown how to implement this algorithm to reach an optimum size of hybrid storage for solar water pumping for a site in Iran. In the end, a conclusion of the results of the proposed systems are given.

3.3 Hybrid Storage System

The proposed hybrid system consists of a few strings of batteries and a water tank. The batteries can be charged during the early morning and late afternoon, save any excess energy during the day and provide power to the water pump whenever needed. The water tank is used to store excess pumped water and discharge water in case of pump failure or unexpected water demand. A simple schematic of this hybrid storage system is depicted in figure 23.

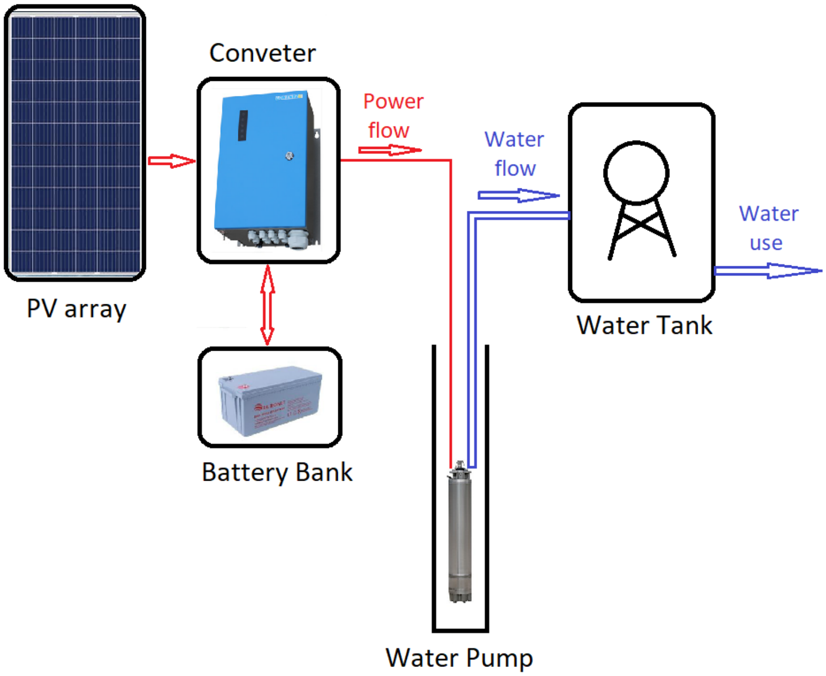


Figure 23: Schematic of a water pumping system with a hybrid storage

This system is proposed for a site near Mashhad in northeastern Iran; this site's approximate area is two hectares, which is divided into 20 cherry and apple gardens with shared water well [1]. Currently, they use diesel generators (figure 24) to provide power to the water pump which this research aims to replace it with an affordable and efficient solar water pumping.

Figure 24: Primary diesel generator which is used in this site

3.4 Define Optimization Problem

The advantage of a hybrid storage system is expressed above. The question has still remained what is the most optimum size of the battery bank and what is the best capacity for the water tank to reduce the system cost while meeting the minimum needed back-up for solar water pumping to guarantee the system reliability; clearly, this is an optimization problem. Like any other optimization problem, first, it is necessary to determine the objective function (which can be called cost function because here is a minimization problem) and constraints that might be linear, nonlinear, equal, or unequal. In the following, the optimization problem is expressed for a hybrid storage system of solar water pumping for the site under study.

3.4.1 Cost function

In this research, like some other work such as [2], Life-Cycle Cost Analysis (LCCA) is considered as the cost function:

$$LCCA = C_C + C_{O\&M} + C_R$$

Where:

- C_C=Capital cost
- $C_{O\&M}$=Operation and maintenance expenses
- C_R=Replacement cost during the project lifetime

- *Note 1:* According to Homer pro simulation for this site in Iran, the mean battery depth of discharge is approximately %15. Also, based on the battery manufacturer company, if %15 of battery capacity is used, the battery lifetime will be more than 2000 cycles (figure 25). Since the operation period in this site is about five months per year, there is no need to replace the batteries during the project lifetime, as shown in Homer pro results in figure 26.

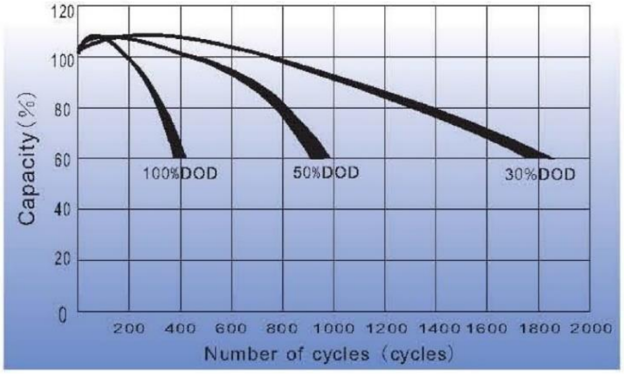
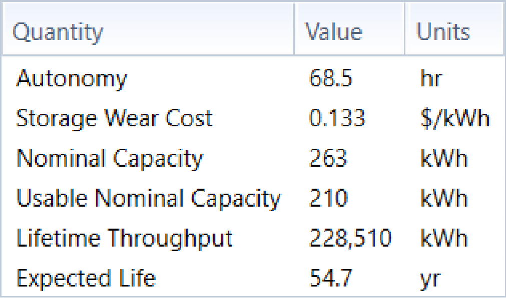


Figure 25: Life characteristics of cyclic use for Euronet Gel Battery

The water tanks are last long, and there is no need to replace them during the project lifetime. Thus, the term C_R can be omitted in the LCCA function.



Quantity	Value	Units
Autonomy	68.5	hr
Storage Wear Cost	0.133	$/kWh
Nominal Capacity	263	kWh
Usable Nominal Capacity	210	kWh
Lifetime Throughput	228,510	kWh
Expected Life	54.7	yr

Figure 26: Results of Homer pro battery analysis

- *Note 2:* the used batteries are gel batteries which unlike the conventional lead-acid batteries, they do not need to charge after each period of use. In addition, the water tanks have no specific operation or maintenance cost. As a result, the term $C_{O\&M}$ is relatively small, so that it can be omitted as well.

For this specific site in Iran, the sum of the capital cost of water tanks and batteries is considered as a cost function:

$$Cost\ fuction = \ P_B + P_T\ ;\ \begin{cases} P_B\ = Price\ of\ batteries \\ P_T\ = price\ of\ water\ tanks \end{cases}$$

3.4.2 Constraints

The only constraint in this problem is that there should be enough stored energy, whether in the form of chemical energy in batteries or potential energy of stored water in tanks, to ensure the reliability of the solar water pumping system during the operation period on the site in Iran. The best source to find this minimum needed energy is Homer pro simulation because Homer calculation is based on accurate data for the ambient condition on the site in addition to battery specifications. Based on Homer simulation, the minimum stored is calculated:

1) Homer suggestion for total size of the battery bank for the site in Iran is 240 KWh
2) Just 80% of the battery capacity is allowed to use (min SoC is 20%); also, the efficiency of this battery is 85%; so the minimum needed stored energy is:

$$minimum\ needed\ stored\ energy = 240\ KWh\ \times 0.80\ \times 0.85 = \mathbf{163.2\ KWh}$$

It is found that this solar water pumping in Iran needs at-least 163.2 KWh of stored energy. As a result, the constrain for this optimization problem is:

$$((E_B + E_T) - 163.2) \leq\ \varepsilon$$

Where:

- E_B is the stored energy in batteries
- E_T is the stored energy in water tank

- ε is a small positive number. In this paper, it is considered as five percent of the minimum needed energy to ensure daily water demand is satisfied.

$$\varepsilon = 163.2 \times 0.05$$

The following procedure is taken to calculate the stored potential energy in the battery and water tanks:

Stored energy in battery: To calculate the total stored energy in batteries, simply can multiply number of used batteries to the ampere-hour of each battery times voltage of each battery:

E_B (Wh) = # of batteries× 100 Ah × 12 V

Stored energy in water tank: The potential stored energy in water tank can be obtained based on injected water into the tank by water pump. To do so, first, divide tank capacity by rated water flow to see how many hours it takes to fill this water tank; then, multiply the water pump's nominal power to calculate hours to obtain the energy consumed by pump to pump sufficient water to the tank. This energy is called the *stored capacity* of the tank [3]:

E_T (KWh) = Tank capacity (m^3) ÷ 27 (m^3/h) × 22 (KW)

3.5 Imperialist Competitive Algorithm (ICA)

Imperialist Competitive Algorithm (ICA) is an evolutionary algorithm which is proposed by Esmaeil Atashpaz-Gargari in the year 2007 [4]. This optimization algorithm is inspired by imperialist competition on their properties. This algorithm starts with a random initial point called “country”; countries are divided into two groups, imperialists and colonies which each colony belongs to an imperialist. During the run of this algorithm, imperialists start a competition with other imperialists to take power over more colonies. In the end, the most powerful imperialists take control over all countries and converge them to an optimum global point. In this section, an overview of ICA is expressed, and flowchart of this algorithm is shown in figure 27.

3.5.1 Initialization

In the beginning, the algorithm generates Npop (number of total countries in the world) random initial countries which each country is defined as a 1×Nvar array where Nvar is the number of variables of intended optimization problem; each element of this array represent a property of that country like race, language, and so on [4].

$$country = [P_{race}, P_{language}, \dots, P_{N_{var}}]$$

The algorithm calculates the power of each country by evaluating the objective function and then ranks the countries according to their power (a country with higher fitness is more powerful).

$$fitness = \ objective\ function\ (country) = f(P_{race}, P_{language}, \dots, P_{N_{var}})$$

Then Nimp (number of imperialists) of most powerful countries are selected as imperialists and the rest of the population (Ncol) as colonies. Afterward, all colonies are divided among imperialists such that an imperialist with a higher power must have more chances to get more colonies[4].

$$N_{col} = N_{pop} - N_{imp}$$

In this research, to divide colonies among imperialists, the Roulette Wheel selection is used; casinos' roulette inspires this method. This wheel is like a pie divided into different partitions, representing the normalized power of an imperialist.

$$Normalized\ power\ of\ imperialist\ k^{th} = 1 - \frac{Cost\ (imperialist\ k^{th})}{\sum_{i=1}^{N_{imp}} Cost\ (imperialist\ i^{th})}$$

A random number between 0 and 100% is generated to select an imperialist and allocate a colony to that imperialist. In this way, an imperialist with a higher power has a higher chance to be selected; as a result, an imperialist with a higher power has more colonies. Figure 28 is an example that shows the second imperialist is the most powerful imperialist; as a result, it has the most share in nominalized probability.

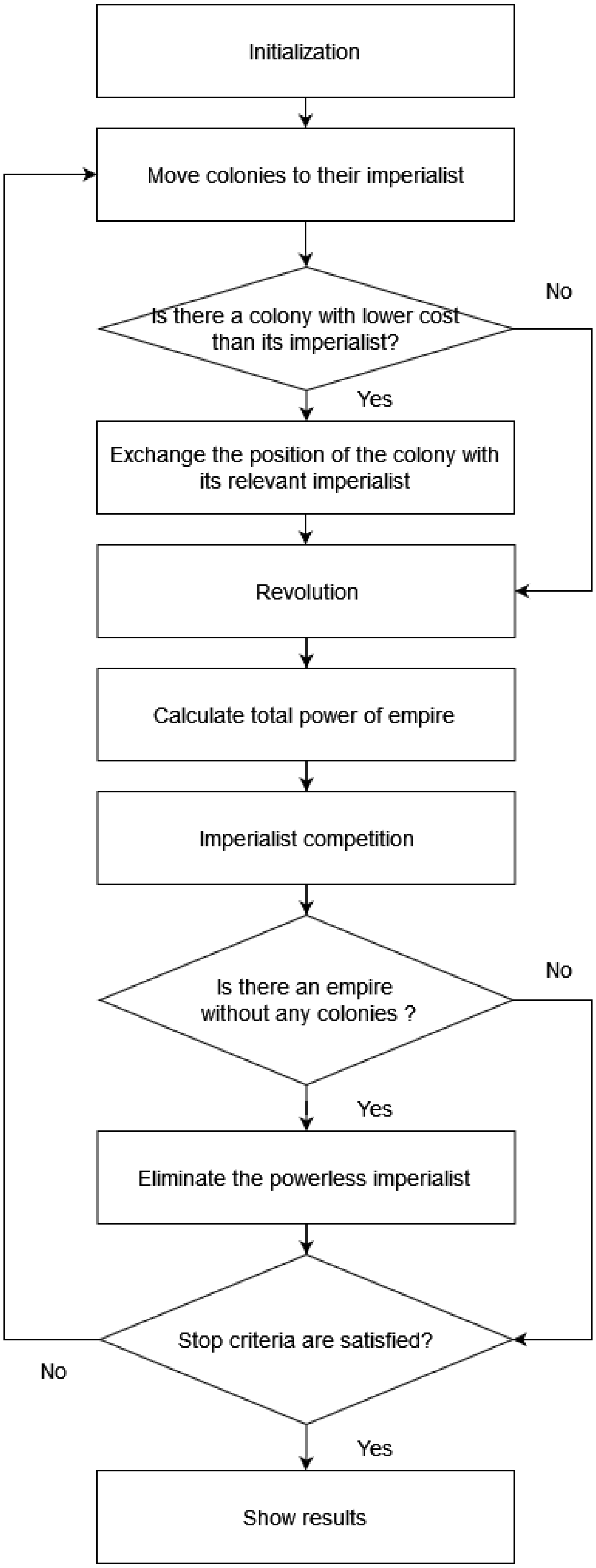


Figure 27: ICA flowchart

3.5.2 Colonies moving toward their imperialist

Imperialists try to make their empire more powerful by moving their colonies toward themselves; in this way the total power of the empire will rise, so the chance of winning that imperialist in the competition will be increased, which will result in empire expansion.

To move a colony toward its imperialist the following function is defined:

$$x = \beta \times rand \times d\ ;$$

$$\begin{cases} \beta = moving\ coefficient \\ d = distance\ between\ imperialist\ k^{th}\ and\ colony\ h^{th} \end{cases}$$

$$new\ position\ of\ colony\ h^{th} = old\ position\ of\ colony\ h^{th} + x$$

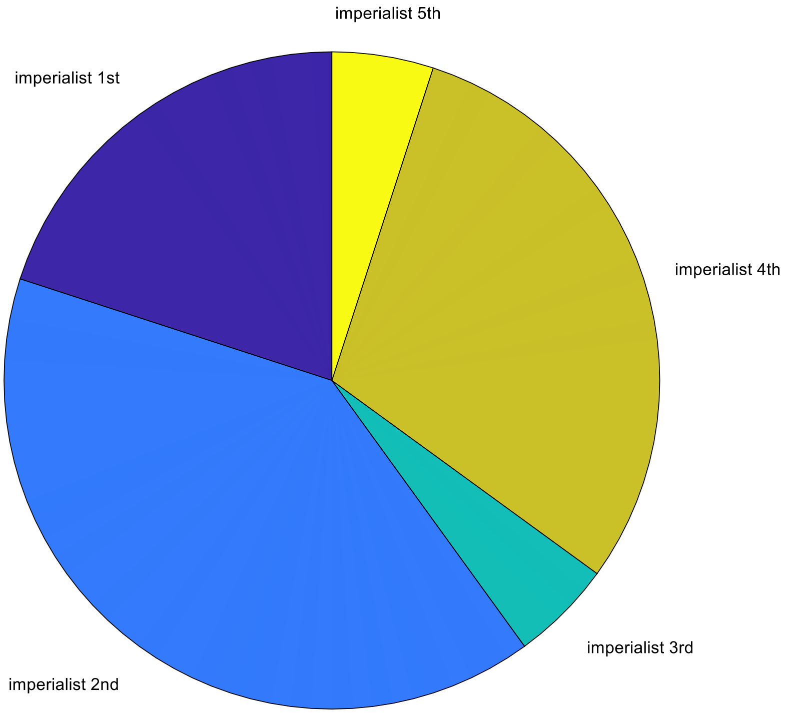


Figure 28: The nominalized probability of imperialists

3.5.3 Exchange the position of a colony with its relevant imperialist

After a colony moves toward its imperialist, it may find a better location in the search area with higher fitness than the imperialist; in this scenario, the position of the imperialist and that colony will be switched [5].

3.5.4 Total power of an empire calculation

The total power of an empire is defined as the sum of the power of the imperialist of the empire and a coefficient of the mean power of all colonies of the empire[4]:

$$\begin{aligned} &Total\ Power\ of\ Empire\ k^{th} \\ &\qquad = power\ imperialist\ k^{th} + \zeta \times \left(\frac{\sum_{i=1}^{N_{col}} Fitness(colony\ i^{th})}{N_{col}}\right) \end{aligned}$$

ζ is a constant coefficient (0< ζ<1) that determines the share of colonies' power in the empire's total power. Small zeta means imperialist power has the most effect on total power and large zeta means the effect of colonies' power is considered.

3.5.5 Imperialist competition

As is clear from the name of this algorithm, this step of the algorithm is the most important step. In the competition among imperialists, they try to take control over more colonies in other empires to increase their empire power. During this competition, the weakest empire has the most likelihood of losing colonies and the most powerful empire has more chance of owning more colonies.

In this algorithm, the weakest colony in the weakest empire is picked. It is given to the selected empire using the roulette wheel, which means that an empire with the most total power has more probability of owning the weakest colony [4].

3.5.6 Eliminating the powerless imperialist

During the run of the algorithm and after a couple of loops, an imperialist might lose all of its colonies; in this case, the relevant empire will be collapsed, then imperialist will be considered a colony and it will be assigned to one of the rest empires with roulette wheel selection [4].

3.5.7 Stop criteria

Stop criteria can be defined in different ways depending on the nature of the optimization problem. In this research, reaching a specific number of algorithm loop (generation) is considered a stop criterion.

3.6 Implementation of ICA for Optimum Size of Hybrid Storage for Solar Water Pumping in Iran

In this section, the properties of used ICA are presented, and the result of optimum sizing is expressed.

3.6.1 ICA initial parameters

The ICA algorithm for this research is programmed and run in MATLAB R2021a. The initial parameter of used ICA is mentioned in the following table:

Table 2: The initial parameter of employed ICA in this research study

Parameter	Value	Note
Number of countries' property	2	There are two variables: battery and water tank
Number of countries	30	
Number of Imperialists	5	
Lower and Upper Bound of Battery Value	[0 200]	# of batteries
Lower and Upper Bound of water tank Value	[0 200]	In m3
Moving coefficient (β)	2	
Weight of mean cost of Colonies (ζ)	0.1	
Maximum number of iterations	10000	
Percent of Revolution	0.2	
probability of revolution operation	0.2	
probability of revolution on each colony	0.4	

The initial population is generated uniformly randomly.

3.6.2 Search area

In this research, a lookup table consisting of prices of batteries and water tanks in different capacities is given to the algorithm as input; the algorithm performs a linear interpolation method to build a continuous search area.

3.6.3 Cost function and constrain

The cost function in this research is the summation of the price of batteries and water tanks:

$$Cost = price\ of\ batteries + \ price\ of\ water\ tanks$$

A penalty function is defined in order to apply the constraint:

$$if\ \left|\left(\begin{matrix} stored\ energy \\ in\ water\ tanks \end{matrix} + \begin{matrix} stored\ energy \\ in\ batteries \end{matrix}\right) - \begin{matrix} min\ needed \\ stored\ energy \end{matrix}\right| \geq \begin{matrix} min\ needed \\ stored\ energy \end{matrix} \times 0.05$$

$$then$$

$$Cost = (price\ of\ batteries + \ price\ of\ water\ tanks) + penalty$$

According to section III, the minimum needed stored energy for the under-study site in Iran is 163.2 KWh. Also, the penalty should be a large number, in this research, it is CA$9,000,000.

3.6.4 Revolution

This auxiliary operation for ICA mimics the mutation operation in the Genetic Algorithm (GA)[6], [7]. This operation takes one colony and moves that randomly in the searching area. Revolution might slow down the algorithm, but it ensures that the ICA will not be stuck in the local optimum.

3.6.5 Results

The algorithm suggestion for optimum size of storage system for this specific solar water pumping system in Iran is as follows:

Table 3: the output results of ICA

storage	Value
Number of batteries	40
Water tank (m^3)	140

Figure 29 illustrates how the best country in the world improved during the algorithm's run; at first, the algorithm found a system size with a cost of more than CA$28,000, and after a couple of loops, it tried to optimize the size of hybrid storage. This improvement happened step by step during the algorithm run, and after the loop 1000, the algorithm reached a steady-state, which means that the most optimum size of the hybrid storage system is found.

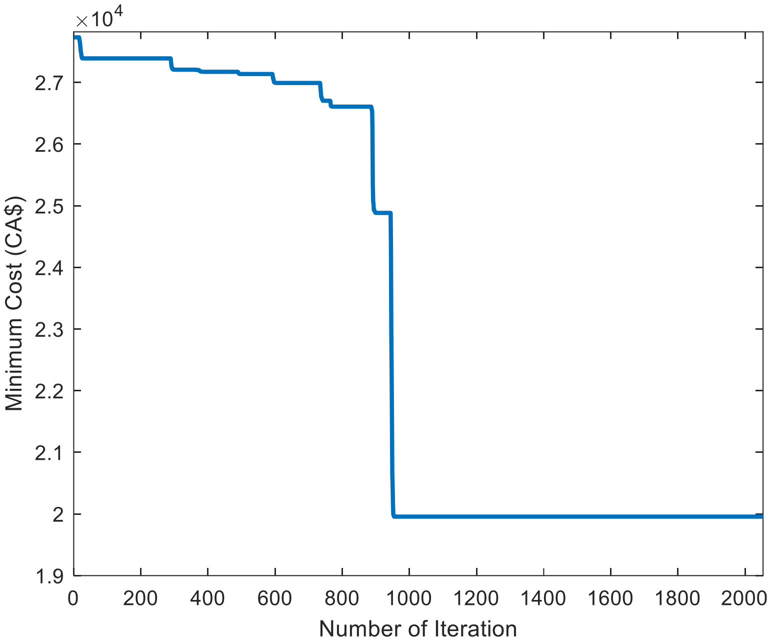


Figure 29: The cost of best imperialist during the run of algorithm

The following calculation can be done to show that the found size of the system can satisfy the constraint:

V_{Bus}= 12V×10 = 120V

Ah of each string is 100 Ah, so total bank Ah= 4×100= 400

Energy in batteries (Wh) = 400×120= 48000= 48 KWh

Energy in batteries (consider energy lost and depth of charge) = 48×0.8×0.85= 32.64 KWh

With 40 batteries, the pump with 22KW power can run for about 1.5 hours (32.64 /22).

This pump can pump about 40.5 m^3 of water (1.5hr × 27(m^3/hr)).

Also, there is a tank with 140 m^3 of water storage.

As a result, this system has 180.5 m^3(40.5+140) water storage

This site in Iran needs about 180 m^3 (188.6 ± 5%) of water as a back-up for one day. So, this system satisfies the water requirement as back-up for this site in Iran.

To justify the output result of ICA, the following table is prepared with a couple of battery and water tank combinations. As can been seen in table 4, if battery is used more, the total cost is high, as the number of batteries decreases and the capacity of water tank increases, the total cost starts to drop. At the minimum point it reaches to lowest cost and after that the cost start to increase. As a result, the optimum size for this specific site in Iran is supposed to be around this point that the ICA found it correctly.

Table 4: Some feasible size of the hybrid storage system

# of batteries	Water tank capacity (m^3)	Total Price (CA$)
130	9	26562
120	24	25509
110	39	24483
100	55	23757
90	68	22760
80	82	21860
70	97	21366
60	112	20699
50	128	20448
40	140	20041
40	141	20342
40	142	20644
40	143	20945
30	156	22862

30	158	23464
20	170	24905
20	171	25188
10	184	26540
10	185	26740

3.6.6 Comparison

As expressed in table 5, using a hybrid storage system with 40 batteries (each battery 100 Ah) and a 140 m^3 water tank, the total cost is approximately CA$20,000, which is cheaper than the two other configurations.

Table 5: comparison of storage methods

Storage type	capacity	Cost (CA$)
batteries (Number of 100 Ah battery)	200	40,000
Water tank (m^3)	180	23,800
Hybrid	Batteries: 40 × 100Ah and Water tank: 140 m^3	20,041

Although the difference between hybrid storage and only water tank storage is not significant, the hybrid system boosts system reliability and can provide sufficient water during the hours of operation.

3.7 Conclusion

In this paper, a hybrid storage system is proposed for a site in Iran. It is discussed that a hybrid storage system can take advantage of both battery and water tank at the same time, resulting in lower cost and higher system availability.

Also, ICA is employed to find an optimum size of the system. It not only guarantees the minimum needed storage, but also reduces the cost of the storage system. The algorithm suggests a hybrid storage system consisting of 40 batteries and 140 m3 water tank; this is the cheapest configuration for the site in Iran, which can satisfy the minimum needed storage.

This research shows that a hybrid storage system can be more economical in comparison to conventional configurations for storage systems in solar water pumping.

3.8 Acknowledgment

The authors kindly thank Roshana Gostar Shargh Barsava for providing funding for this research.

References

[1] A. Jahanfar and M. Tariq Iqbal, "A Comparative Study of Solar Water Pump Storage Systems," 2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC), 2022, pp. 1070-1075, doi: 10.1109/CCWC54503.2022.9720912.

[2] C. Soenen et al., “Comparison of Tank and Battery Storages for Photovoltaic Water Pumping,” Energies, vol. 14, no. 9, p. 2483, 2021.

[3] U. Ashraf and M. T. Iqbal, “Optimised Design and Analysis of Solar Water Pumping Systems for Pakistani Conditions,” Energy Power Eng., vol. 12, no. 10, p. 521, 2020.

[4] E. Atashpaz-Gargari and C. Lucas, “Imperialist competitive algorithm: An algorithm for optimization inspired by imperialistic competition,” in 2007 IEEE Congress on Evolutionary Computation, 2007, pp. 4661–4667, doi: 10.1109/CEC.2007.4425083.

[5] S. Nazari-Shirkouhi, H. Eivazy, R. Ghodsi, K. Rezaie, and E. Atashpaz-Gargari, “Solving the integrated product mix-outsourcing problem using the Imperialist Competitive Algorithm,” Expert Syst. Appl., vol. 37, no. 12, pp. 7615–7626, 2010, doi: https://doi.org/10.1016/j.eswa.2010.04.081.

[6] Z. Pan, D. Lei, and Q. Zhang, “A New Imperialist Competitive Algorithm for Multiobjective Low Carbon Parallel Machines Scheduling,” Math. Probl. Eng., vol. 2018, p. 5914360, 2018, doi: 10.1155/2018/5914360.

[7] R. L. Haupt and S. E. Haupt, Practical genetic algorithms. John Wiley & Sons, 2004, pp 43-44.

Chapter 4: Dynamic Modeling and Simulation of Solar Water Pumping With Hybrid Storage System

A version of this manuscript has been peer-reviewed, accepted, and presented in 2022 IEEE 13th Annual Information Technology, Electronics and Mobile Communication Conference. The paper has also been published on IEEE Xplore Database as a part of 2022 IEEE 13th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON). I am the primary author, and I carried out most of the research work performed the literature reviews, carried out the system design, implementations, and analysis of the results. I also prepared the first draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired, provided the research guide, reviewed and corrected the manuscript, and contributed research ideas to the actualization of the manuscript.

4.1 Abstract

Due to the energy crisis and surge in the price of energy, using renewable energy sources has become a trend these days. Ironically, in many Middle East countries like Iran, they still use diesel generators to power their water pumps while they have a good potential for solar energy. In the authors' previous work, an optimum solar water pump with a hybrid

storage system was proposed, and its feature were presented. Like any other feasible project, it is necessary to simulate the system to examine its stability and analyze system in details. To do so, in this paper, an exact system component model is implemented on Simulink, and the result of dynamic analysis are provided. It is shown that the water pump works properly in different circumstances, and it is a trustable system to substitute with traditional water pumping systems.

4.2 Introduction

The rapid increase in the price of diesel and the high maintenance cost of diesel generators are two significant encouragements to immigrate from conventional pumping systems to solar water pumping systems, especially in remote areas with high potential for solar energy. High Global Horizontal Irradiation (GHI) and a notable portion of semi-deep water wells in Iran's water supply make Iran an ideal country for developing a solar water pumping system [1].

In the authors' previous work [2] a solar water pumping for a site near Mashhad in Iran was designed, and steady-state results were presented. To put this idea in practice, a dynamic analysis should be done to guarantee the smooth work of the system. First, it is necessary to have accurate models of components to have a precise result from simulation. In this research, the standard models for dynamic analysis of the system are chosen.

In this paper, first, an overview of solar water pumping with hybrid storage systems is given; then, the dynamic model and mathematical relations of all main components of the system are expressed. In section four, the dynamic simulation is done with the help of

Simulink and the results are provided. In the end, a brief conclusion of the results of the proposed systems and suggestions are given.

4.3 Solar Water Pumping with a Hybrid Storage

In this research, the water pumping system consists of Photovoltaic arrays (PV), a converter, a submersible water pump, battery bank, and water tank. The benefit of this system over other solar water pumping systems is a hybrid storage system that allows pump to operate when it is not sunny.

The hybrid storage system can take advantage of both battery and water tank. In this system, the batteries can be charged in the early morning and late afternoon when the provided power to the pump is less than the running threshold [2]. Also, the water tank can store water and inject it into the irrigation system when needed. Since this hybrid storage system decreases the project expenses, it encourages farmers to replace their diesel pumping system with solar water pumping [2]. Figure 30 illustrates the main components of the solar water pumping with a hybrid storage system.

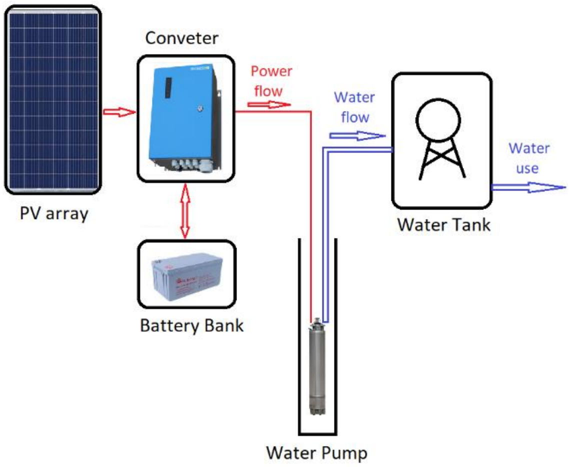


Figure 30: Schematic of a water pumping system with hybrid storage (adapted from [2])

The case study of this research is a site in northeastern Iran. Gardeners use a shared water well to irrigate their cherry and apple trees. The power source for submersible water pump is provided by two diesel generators (one as primary and another as auxiliary). Figure 31 shows the auxiliary diesel generator which currently is use on the site.

Figure 31: Diesel generators which is used to provide power for the water pump

4.4 Dynamic Modeling and Component Specification of The Solar water Pumping System

4.4.1 Photovoltaic (PV)

The photo voltaic unit is the most fundamental part of the system, providing the power for the whole system. A PV unit can be seen in three scales: PV cells, modules and arrays. This section is present the mathematical model from a single PV cell to PV arrays.

Photovoltaic cell: a common single diode model of a solar cell can be divided from physical principles and laws [3]. Figure 32 shows the equivalent circuit of a solar cell (one diod model).

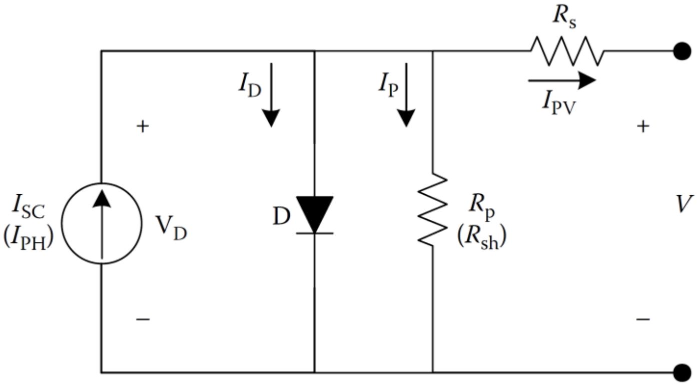


Figure 32: PV cell single diode equivalent circuit (adapted from [4])

the mathematical equations can be divided from the above circuit with the help of Kirchhoff's circuit laws and Shockley diode equation [5], [6]:

$$I_{PV} = I_{SC} - I_0\left(e^{\frac{q}{KT}(V+I_{PV}R_S)} - 1\right) - \frac{V + I_{PV}R_S}{R_P}$$

Where:

- I_0 = Reverse bias saturation current
- q = Electron charge
- K = Boltzmann constant
- T = Cell temperature in Kelvin

This equation shows the relationship between the current and voltage of a solar cell. It should be noted that since IPV has emerged on both sides of the equation, this is an implicit equation.

Another factor which is considered in simulation is the impact of ambient conditions. Since PV cells are made from semiconductors, temperature and solar irradiance directly impact PV output voltage and current. The impact of temperature is more on open circuit voltage and impact of changes in irradiance is more on short circuit current [6]. For example, a drop in solar irradiance will result in a decline in short circuit current and a negligible decrease in open circuit voltage. Figure 33 depicts a few examples of changes in ambient conditions.

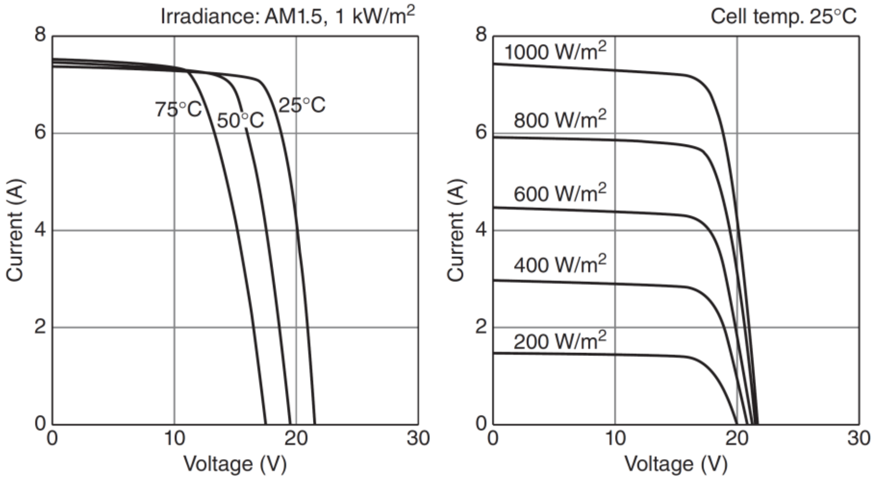


Figure 33: Impact of changes in temperature of solar cell and sun irradiance in output voltage and current of a PV module (adopted from [6])

In Simulink, a PV array model consisting of 140 panels with 340 W nominal power (14 parallel strings and each string consisting of 10 modules in series) is used. The DC bus nominal voltage is 240.

4.4.2 Power conversion

In this research, two-stage power conversion is used to provide power in constant voltage and frequency to the water pump (figure 34).

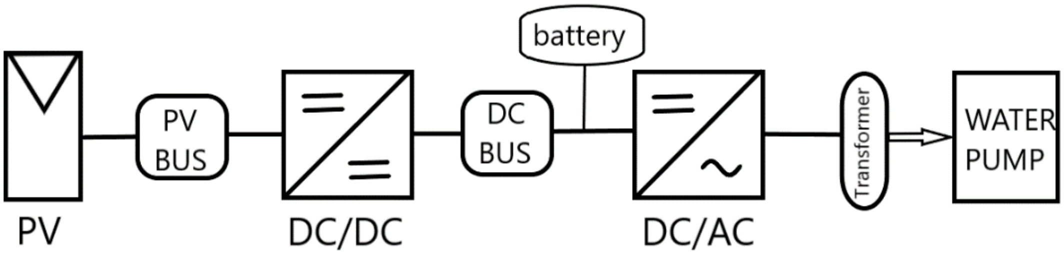


Figure 34: Power conversion schematic for the solar water pumping system

Buck DC/DC converter: A buck converter is used to step down the output voltage of PV arrays to a constant 240V DC; this power interface is essential for charging the batteries and keep the operating point at maximum power. Figure 35 illustrates the circuit of a buck converter:

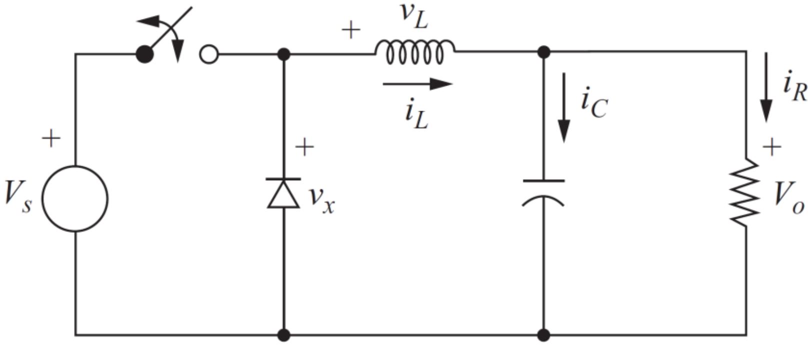


Figure 35: Buck converter topology (adopted from [7])

The relation between input voltage (VS) and output voltage (VO) can simply be expressed as follow [7]:

$$V_O = V_S D$$

Where D is duty cycle. Figure 36 depicts the implemented model of buck converter and MPPT in Simulink.

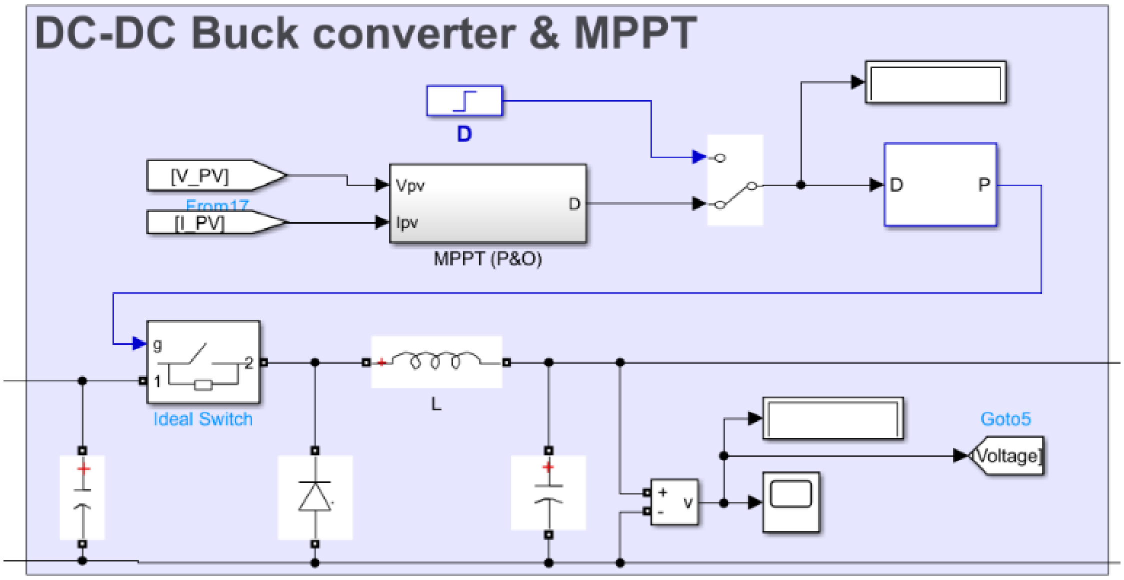


Figure 36: Simulink model of DC-to-DC buck converter and MPPT

DC/AC converter: In this research, a typical two-level inverter is considered, which provides a three-phase AC power for the water pump. This configuration, which is shown in figure 37, is called two-level because the output voltages (V_{a0}, V_{b0} and V_{c0}) can take two-level voltage, V_{bus} or 0 [8].

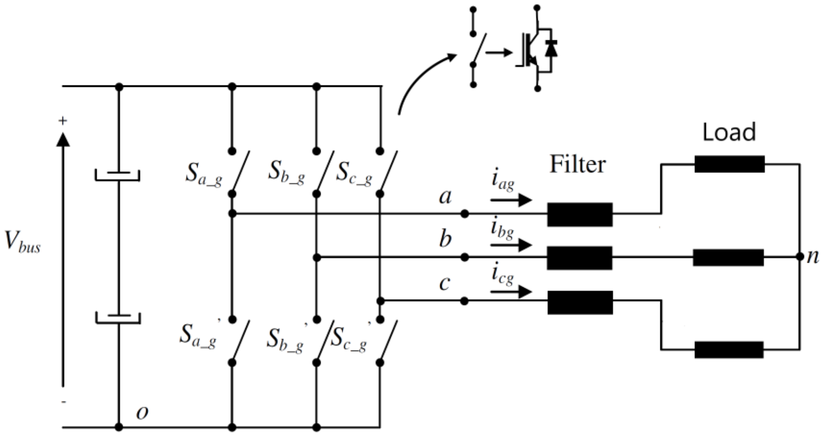


Figure 37: Two-level 3ph inverter (adopted and modified from [8])

To find equations that express the relation between output voltages and input voltages, the following procedure can be taken [8]:

First, to find a relation between line and phase voltage of each phase, the following equivalent single-phase in figure 38 is considered:

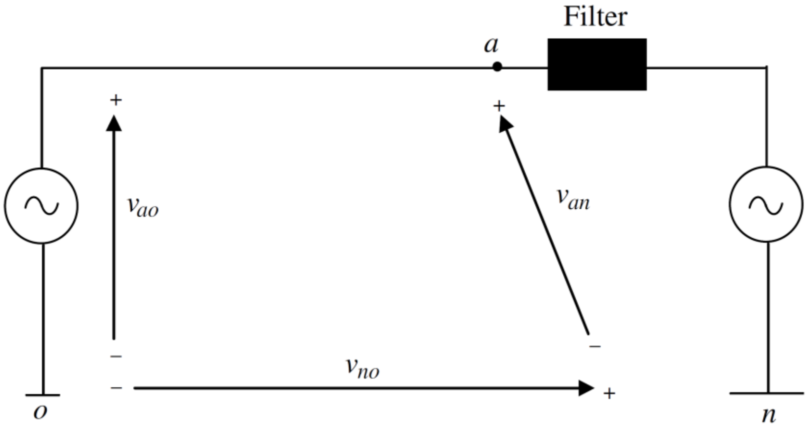


Figure 38: a single-phase circuit of phase a (adopted from [8])

From KVL in this circuit:

$$V_{an} = V_{a0} - V_{n0}$$

This equation is true for all phases. Also, it is assumed that the load is symmetric, so:

$$V_{an} + V_{bn} + V_{cn} = 0$$

After substituting these equations, it yields:

$$V_{n0} = \frac{1}{3}(V_{a0} + V_{b0} + V_{c0})$$

From these three equations:

$$V_{an} = \frac{2}{3}V_{a0} - \frac{1}{3}(V_{b0} + V_{c0})$$

$$V_{bn} = \frac{2}{3}V_{b0} - \frac{1}{3}(V_{a0} + V_{c0})$$

$$V_{cn} = \frac{2}{3}V_{c0} - \frac{1}{3}(V_{b0} + V_{a0})$$

From figure 37, it is clear that $V_{j0} = V_{bus}S_{j\_g}$ where j=a, b, c. So:

$$V_{an} = \frac{V_{bus}}{3}(2S_{a\_g} - S_{b\_g} - S_{c\_g})$$

$$V_{bn} = \frac{V_{bus}}{3}(2S_{b\_g} - S_{a\_g} - S_{c\_g})$$

$$V_{cn} = \frac{V_{bus}}{3}(2S_{c\_g} - S_{b\_g} - S_{a\_g})$$

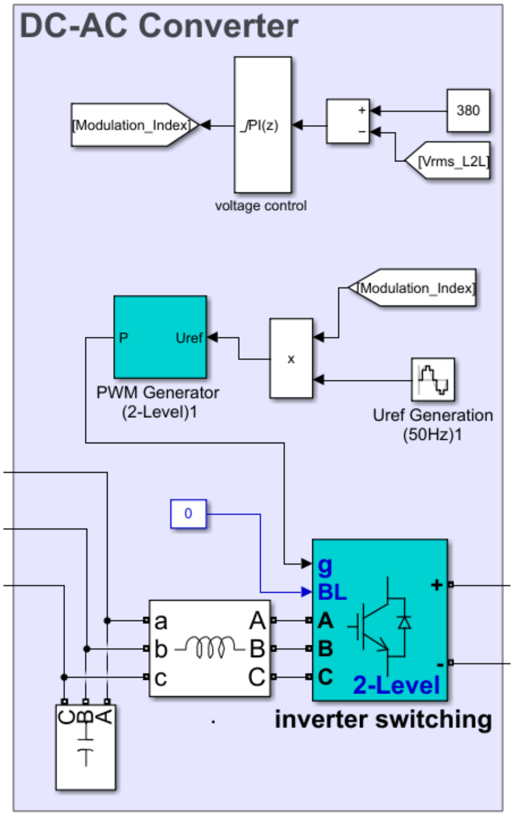


Figure 39: the Simulink model of two-level DC to AC inverter

In this model, a PI controller is designed to adjust the modulation index of the inverter regarding to load changes. Figure 39 shows this inverter and its PI controller implementation in Simulink.

4.4.3 Maximum Power Point Tracking (MPPT)

As it discussed, both irradiation and temperature impact PV output voltage and current. In order to keep PV operating point at maximum power in different ambient conditions, a technique should be employed to control the duty cycle of DC-to-DC converter [1]. In this research, Perturb-and-Observe (P&O) tracking method is used to keep the operating point at maximum power point:

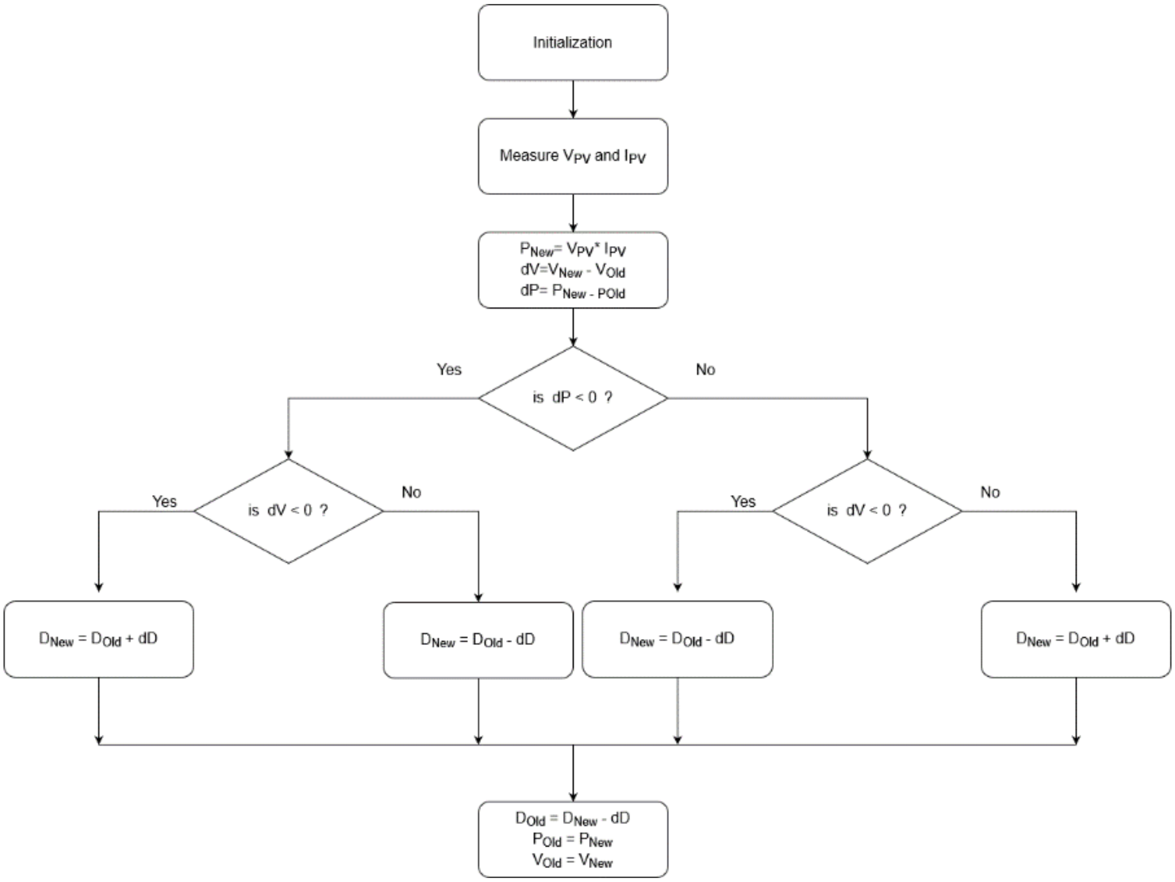


Figure 40: P&O flowchart

In Simulink, this algorithm (figure 40) is applied using function block and MATLAB input and out.

4.4.4 Water pump and Water tank

In this research, Lorentz PSK2-40 is considered as a water pump which meets the minimum needed water flow (27 m3/hour) and Total Dynamic Head of 170 m (TDH) for that site. In Simulink, this is models with a three-phase asynchronous motor and a centrifugal pump.

To simulate the difference in height of well and water tank, two tank in different pressure is considered (h=170m) :

$$Pressure = \rho g h = 1000 \times 9.81 \times 170 = 1667700\, pa$$

Figure 41 shows the Simulink modelling of water pump and water tank. In this model, piping friction is considered with two pipe lines, one for vertical and another for horizontal.

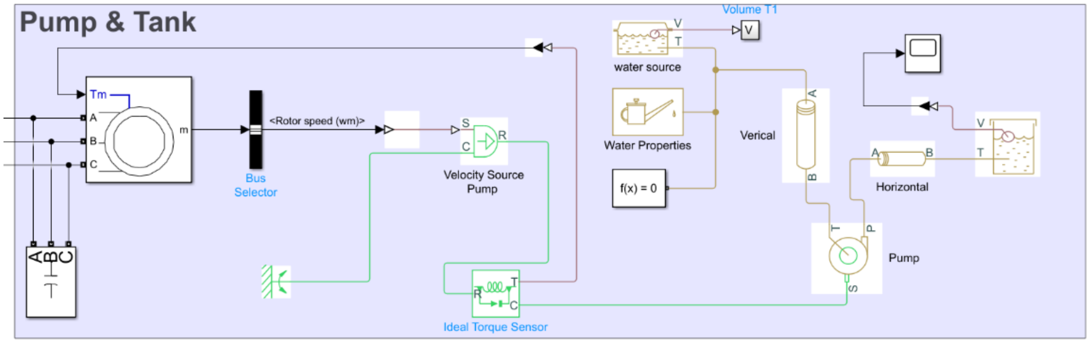


Figure 41: Simulink model of water pump and water tanks

4.4.5 Battery

Batteries are connected to DC bus to inject power to the system when needed or save excess energy in the system maintain the voltage in an acceptable level. For this research, gel batteries are used due to the high lifespan and low maintenance cost.

4.5 Results of Dynamic Simulation in Simulink

The performance of the proposed solar water pump is evaluated on MATLAB Simulink at Standard Test Condition (STC) that cell temperature is 25 Celsius and irradiance is 1000 w/m^2. Figure 42 illustrates the full system model on Simulink.

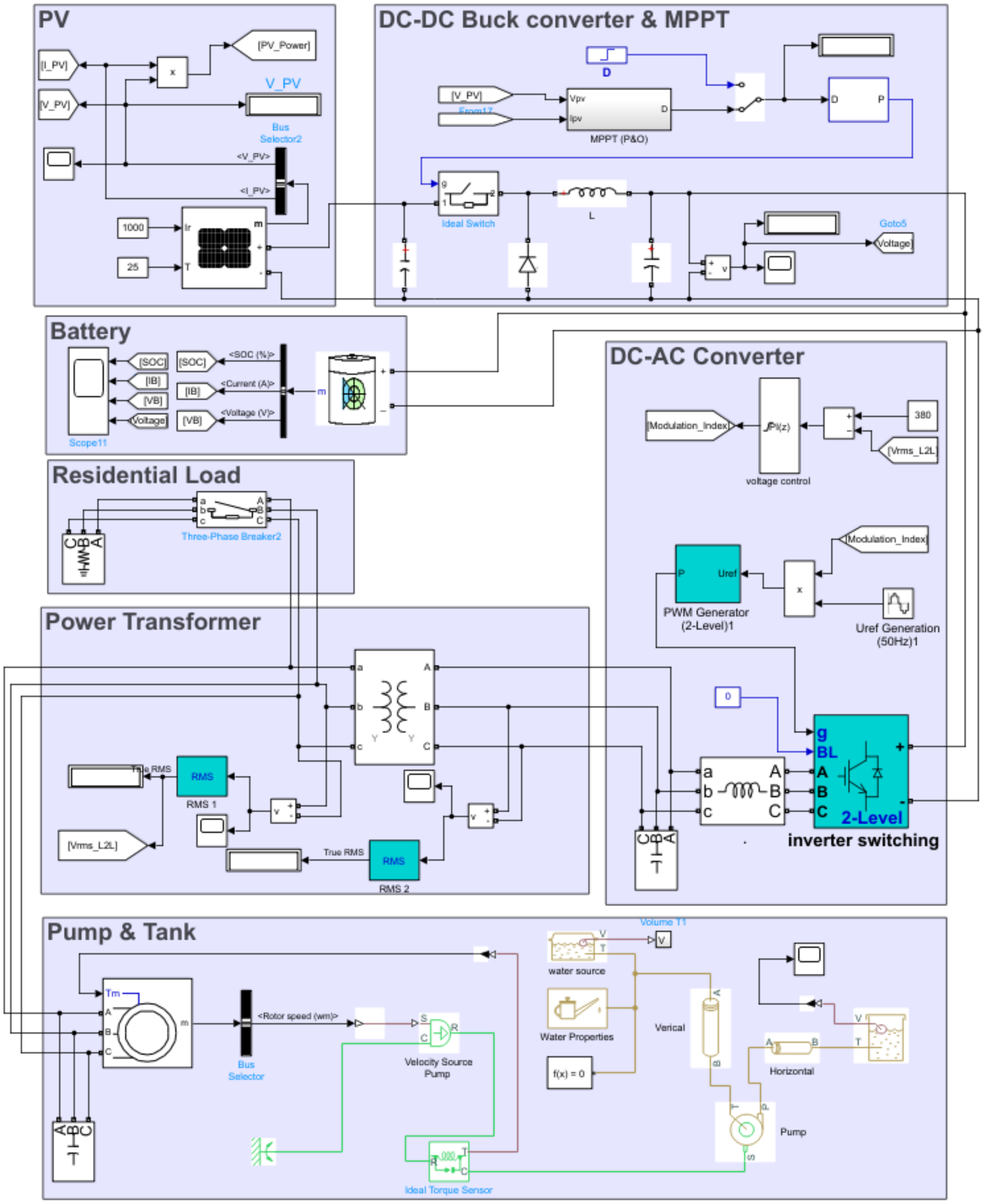


Figure 42: the complete model of solar water pump system with hybrid storage system in Simulink

As it is shown in figure 43, the system works properly and a sinusoidal three-phase voltage feeds water pump; as a result water is pumped in the tank and water lever increase slowly in the tank (figure 44).

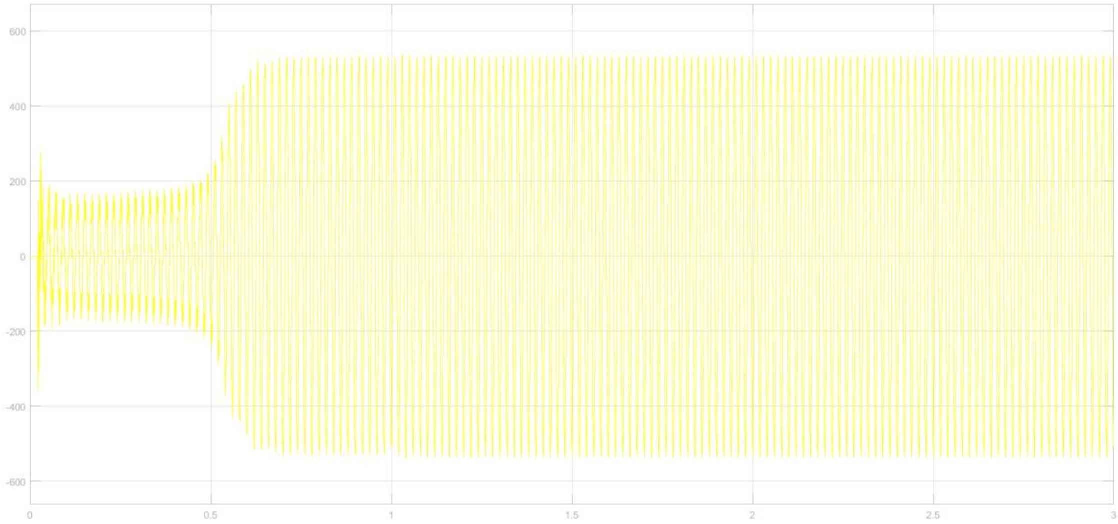


Figure 43: V_{L-L} phase b and c

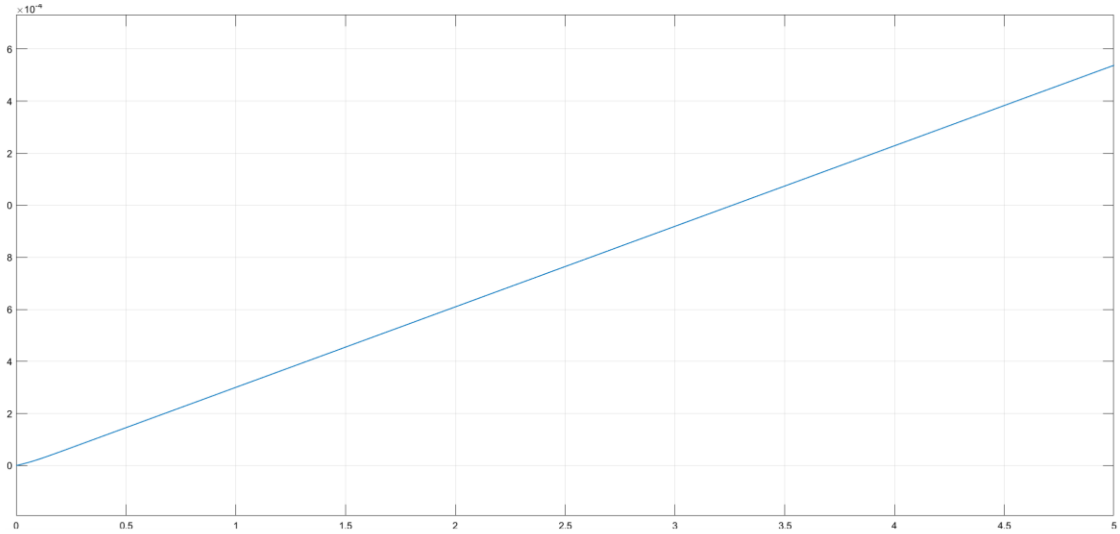


Figure 44: Water level in the tank

To evaluate the system stability in load changes, a small active load (3 KW) is switched at second one. As it can be seen in figure 45, at second 1, there is a small change in voltage but after that it back to normal operation.

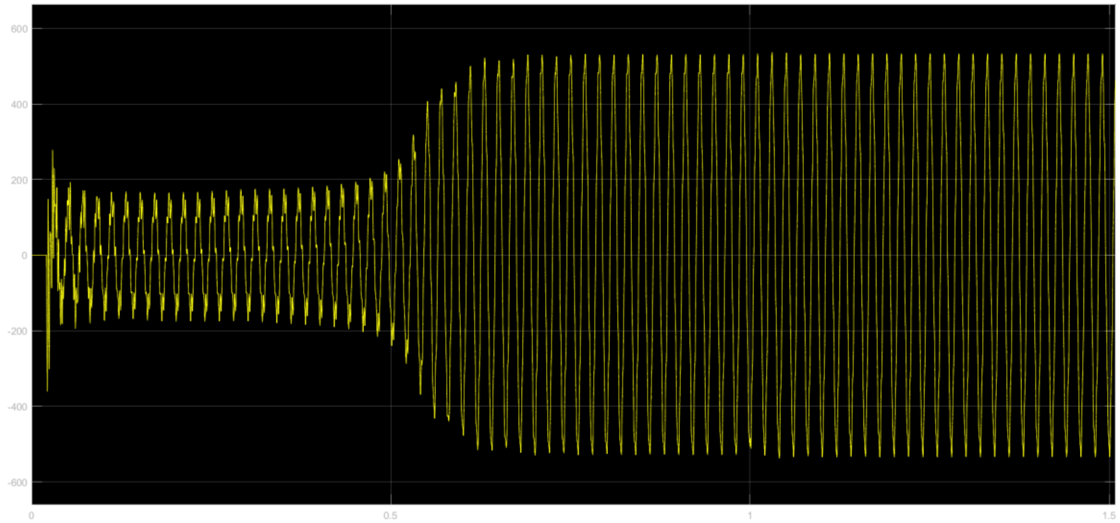


Figure 45: V_{L-L} phase b and c (switch at 1 second)

To see the MPPT operation, the irradiance is changed every 0.5 second. Figure 46 shows that the MPPT track the changes correctly and changes the duty cycle of DC to DC buck converter and as result the voltage of DC bus is kept almost constance.

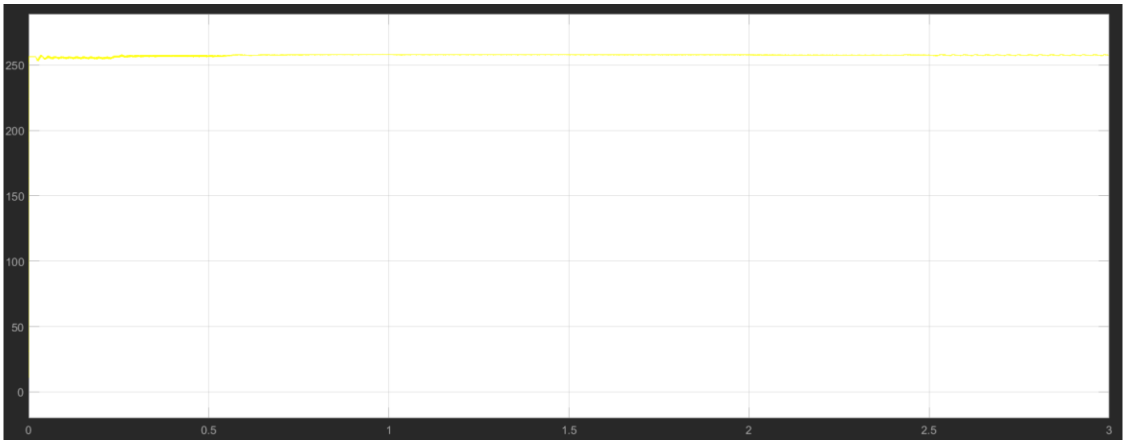


Figure 46: Voltage of DC bus

Since the site's weather is warm and dry, and also the changes of temperature during the day time is significant, the temperature analysis is fundamental. Thus, during the simulation, the temperature changes from low to high and from high low. It is observed that in figure 47, changes in temperature don't have a significant effect on system output and can operate smoothly in all conditions.

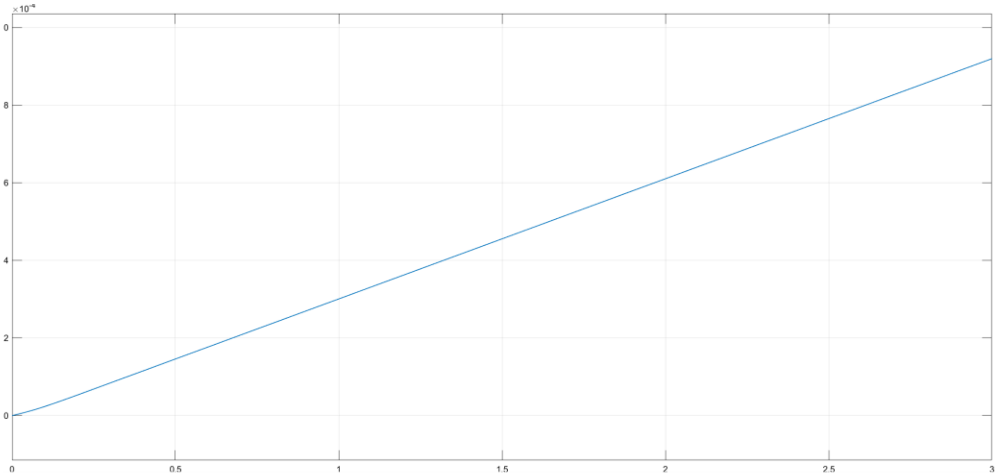


Figure 47: Water level in the tank during the temperature changes

4.6 Conclusion

In this paper, the model of all components of a solar water pumping system with hybrid storage system was presented and the simulation was done with the help of Simulink. The result of dynamic analysis was expressed, and it is shown that the system is reliable in different weather conditions and it is stable in load changing.

This solar water pump is equipped with a hybrid storage system which not only decreases the project cost but also increases the system's reliability. This system was designed and proposed for a specific site in Iran but it is suggested for any other irrigation site with high solar energy potential.

4.7 Acknowledgement

The authors kindly thank Roshana Gostar Shargh Barsava for providing funding for this research.

References

[1] A. Jahanfar and M. T. Iqbal, “A Comparative Study of Solar Water Pump Storage Systems,” in 2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC), 2022, pp. 1070–1075, doi: 10.1109/CCWC54503.2022.9720912.

[2] A. Jahanfar and M. T. Iqbal, “An Optimum Sizing for a Hybrid Storage System in Solar Water Pumping Using ICA,” in 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), 2022, pp. 1–6, doi: 10.1109/IEMTRONICS55184.2022.9795848.

[3] S. Hegedus and A. Luque, “Handbook of Photovoltaic Science and Engineering, Second Edition,” in Handbook of Photovoltaic Science and Engineering, 2011, pp. 1–38.

[4] A. Khaligh and O. Onar, Energy Harvesting: Solar, Wind, and Ocean Energy Conversion Systems. 2017.

[5] S. A. Omidi, G. Rideout, and M. T. Iqbal, “Detailed Bond Graph Modeling of PV-Battery System,” in 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), 2022, pp. 1–7, doi: 10.1109/IEMTRONICS55184.2022.9795811.

[6] G. M. Masters, Renewable and efficient electric power systems [electronic resource] / Gilbert M. Masters., 2nd ed. Hoboken, NJ: John Wiley & Sons Inc., 2013.

[7] D. W. Hart, “Power Electronics,” 2010.

[8] G. Abad, J. Lopez Taberna, M. Rodríguez, L. Marroyo, and G. Iwanski, Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation, vol. 86. 2011.

Chapter 5: Summary and conclusion

5.1 Research Summary

Iran is one of the countries with high energy consumption in the world which the most portion of this is supplied by non-renewable resources, including oil and natural gas. As a result, the toxic and greenhouse gas emissions increased and caused air pollution, especially in big cities, while Iran is among the counties with a high potential for solar energy, which is a clean energy resource and is available even in remote areas.

On the other hand, population growth during the past decades resulted in increased water use, especially in agriculture. Due to the fact that most farms are located in remote areas, and they are supplied by semi-deep or deep water wells, they use diesel generators to provide power for their water pumps.

These issues motivated this research to touch upon solar water pumping to help the environment and secure a clean and reliable energy source in the future. Since the capital cost of the solar-based energy systems are significant, it is necessary to develop optimum solar water pumping systems in order to convince farmers to employ solar water pumping for irrigation.

In this research, first, the optimum sizing of a solar water pumping system was proposed using Homer pro for a site in Iran. The sizing was done for three configurations for storage systems:

1- without storage
2- battery storage system
3- water tank storage system

In the following chapter, a hybrid storage system was proposed, which included both battery and water tank. This hybrid storage system not only slightly decreases the capital cost of the system but also increases the reliability and stability of the system. In order to optimum the size of the batteries and water tank in a hybrid storage system for solar water pump, the ICA was employed as an optimization algorithm (see Appendix A for implemented code in MATLAB). The proposed hybrid storage system included 40 × 100Ah batteries and 140 m^3 of water tank. The estimated price this hybrid storage system was 20,000 CA$.

In the end, to study the system's outcome and ensure the proposed system's correct performance, dynamic analysis was done in MATLAB/Simulink. This simulation consisted of all the system's main units like PV modules, MPPT unit, inverter, battery, water pump and water tank. This simulation showed that the proposed solar water pump with a hybrid storage system was functioning perfectly.

5.2 Future Work

This research was a new development of solar water pumping systems which proposed a hybrid storage system. The suggest future work are:

- Select another site and study the same system.
- Develop and optimum design in building water tanks.

- Employ other optimization algorithms for storage optimization.
- Using a hybrid solar-wind energy system where it has a reasonable potential for wind energy.
- Design data logging and SCADA system
- Design remote control system

5.3 Publications

[1] A. Jahanfar and M. T. Iqbal, "Design and Simulation of a Wind Turbine Powered Electric Car Charging System for St. John's, NL," 2021 IEEE 12th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2021, pp. 0765-0771, doi: 10.1109/IEMCON53756.2021.9623257.

[2] Iqbal, Tariq and Jahanfar, Amirhossein (2021) Design and dynamic simulation of a wind turbine powered electric vehicle charging system. In: 30th IEEE NECEC Conference, November 18, 2021, St. John's, Newfoundland and Labrador.

[3] A. Jahanfar and M. Tariq Iqbal, "A Comparative Study of Solar Water Pump Storage Systems," 2022 IEEE 12th Annual Computing and Communication Workshop and Conference (CCWC), 2022, pp. 1070-1075, doi: 10.1109/CCWC54503.2022.9720912.

[4] A. Jahanfar and M. T. Iqbal, “An Optimum Sizing for a Hybrid Storage System in Solar Water Pumping Using ICA,” in 2022 IEEE International IOT, Electronics and

Mechatronics Conference (IEMTRONICS), 2022, pp. 1–6, doi: 10.1109/IEMTRONICS55184.2022.9795848.

[5] A. Jahanfar and M. T. Iqbal, “Dynamic Modeling and Simulation of Solar Water Pumping With Hybrid Storage System,” in 2022 IEEE 13th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON).

Appendix A:

This is a copy of the code which was used to implement the ICA for optimize the size of hybrid storage system for water pumping system.

```
clc
clear all
close all
%% ICA Parameters
n_Var=2;      % Number of countries' proprty
n_Count=30;   % Number of countries % default=30
n_Imp=5;      % Number of Imperialists % default= 5
n_Col=n_Count-n_Imp; % Number of colonies
BatMin=0; % Lower Bound of Battery Value
BatMax=40000;  % Upper Bound of Battery Value
TanMin=0; % Lower Bound of Battery Value
TanMax=200;  % Upper Bound of Battery Value
beta=2;       % moving coefficient
zeta=0.1;     % weight of mean cost of Colonies
Max_It=200;   % maximum number of iteration
miu=0.2;      %percent Of Revolution % def=0.2
Pr=0.2;      % probabilty of revolution operation % def=0.1
Pr_col=0.4;   % probabilty of revolution on each colony % def=0.4
CostFunction=@(x) Cost(x); % Cost Function
%% Initialization
%defind country structure........................
empty_country.Value=[];
empty_country.Cost=[];
```

```
country=repmat(empty_country,n_Count,1);
%.............................................
%defind Imperialist structure......................
empty_imp.Value=[];
empty_imp.Cost=[];
empty_imp.Col=[];
empty_imp.Total_cost=[];
imp=repmat(empty_imp,n_Imp,1);
%.............................................
for k=1:n_Count
     country(k).Value=[unifrnd(BatMin,BatMax),unifrnd(TanMin,TanMax)];% Initialize
Position
    [country(k).Cost,flag]=CostFunction(country(k).Value);% Evaluation
end
% finding Imperialists and colonies.............
[~, SortOrder]=sort([country.Cost]);% sort costs
country=country(SortOrder); % sort countries


for k=1:n_Imp
    imp(k).Value=country(k).Value;% the best countries are Imperialist
    imp(k).Cost=country(k).Cost;
end
col=country(n_Imp+1:end);% the rest countries are colony
%.............................................
%devide colonies among imperialists.............
% cost wight of Imperialists........................
normilized_probability=zeros(n_Imp,1); %define normilized probability matrix
for k=1:n_Imp
```

```
   normilized_probability(k,1)=1-(imp(k).Cost/sum([imp.Cost]));% 1-sth beacuse its a
min optimazation problem

end

cumulative_proprobability=cumsum(normilized_probability); % calculate cumulative
proprobability of imperialists

%...................................................

% Roulette Wheel Selection...........................

for k=1:n_Col

   r=rand*max(cumulative_proprobability);% beacuse 0<rand<1 but we need a No
between Max and min of cumulative proprobability

   i=find(r<=cumulative_proprobability,1,'first');

   imp(i).Col=[imp(i).Col col(k)]; % add colony to imperialist

end

%...................................................

%% Main

for it=1:Max_It

   % moving the colonies toward their relevant imperialist............

   for k=1:n_Imp

      s=size(imp(k).Col,2);

      for h=1:s


imp(k).Col(h).Value=imp(k).Col(h).Value+[beta*rand(n_Var,1)]'.*(imp(k).Value-
imp(k).Col(h).Value);

            imp(k).Col(h).Value =
[max(imp(k).Col(h).Value(1,1),BatMin),max(imp(k).Col(h).Value(1,2),TanMin)];%
apply upper bound

            imp(k).Col(h).Value =
[min(imp(k).Col(h).Value(1,1),BatMax),min(imp(k).Col(h).Value(1,2),TanMax)]; %
apply lower bound

            [imp(k).Col(h).Cost,flag] = CostFunction(imp(k).Col(h).Value); % evaluate new
cost

      end
```

```
end
%..................................................................
%exchange position of the imperialist and a colony(in case of necessity
for k=1:n_Imp
    [m,p]=min([imp(k).Col.Cost]); %find best colony of kth imperialst
    if m<imp(k).Cost % if cost of best colony was better than its imperialst
        a=imp(k).Value; % save  imperialst position
        b=imp(k).Cost;     %save imperialst cost
        imp(k).Value=imp(k).Col(p).Value;% replace imperialst position with colony position
        imp(k).Cost=imp(k).Col(p).Cost;% replace imperialst cost with colony cost
        imp(k).Col(p).Value=a;% replace colony position with imperialst position
        imp(k).Col(p).Cost=b;% replace colony cost with imperialst cost
    end
end
%.....................................................................
%Revolution(GA:mutation)............................Nabashad behtar ast
if rand<Pr % do revolution or Not in total
    number_of_mutation=ceil(miu*n_Var);
    for h1=1:n_Imp
        s=size(imp(h1).Col,2);
        for h2=1:s
            if rand<Pr_col % do revolution or Not for this colony or not
                mutation_address=randi([1,n_Var],2,number_of_mutation);
                for k=1:number_of_mutation
                    e=imp(h1).Col(h2).Value;
                    if mutation_address(1,k)==1
                    e(mutation_address(1,k))=unifrnd(BatMin,BatMax);
```

```
            elseif mutation_address(1,k)==2
                e(mutation_address(1,k))=unifrnd(TanMin,TanMax);
            end
            imp(h1).Col(h2).Value=e;
          end
        end
      end
    end
  end
  %...............................................
  %calculate total cost of each imperialst and sort.....................
  for k=1:n_Imp
    imp(k).Total_cost=imp(k).Cost+(zeta*mean([imp(k).Col.Cost]));
  end
  [~, SortOrder]=sort([imp.Total_cost]);% sort costs
  imp=imp(SortOrder); % sort imp
  %...................................................................
  if n_Imp~=1 % if we have just one imperialist, we shold skip these steps
    % Imperialistic Competition........................................
    [~,p]=max([imp(n_Imp).Col.Cost]); %worst imperialst is last one(after sort)
    weakest_col=imp(n_Imp).Col(p);% find worst colony of worst imperialst and save it
    imp(n_Imp).Col(p)=[]; % delet worst colony
    for k=1:(n_Imp-1)
      normilized_probability(k,1)=1-(imp(k).Total_cost/sum([imp.Total_cost]));
      if sum([imp.Total_cost])==0 % in case of all cost of colonies be zero(usaully at
the end steps of algotithm)
        normilized_probability(k,1)=1;
      end
```

```
        end
        cumulative_proprobability=cumsum(normilized_probability);
        r=rand*max(cumulative_proprobability);
        i=find(r<=cumulative_proprobability,1,'first'); %Roulette Wheel
        imp(i).Col=[imp(i).Col weakest_col]; % give worst colony to another imperialsit
        %..................................................................
        % Eliminating the Powerless Empires.................................
        [~, SortOrder]=sort([imp.Total_cost]);% sort costs
        imp=imp(SortOrder); % sort imp
        for k=1:(n_Imp)
            s=size(imp(k).Col,2);% find number of colonies
            if s==0 % means imperialst has no colony
                % give it to best imperialst........
                s=size(imp(1).Col,2);
                imp(1).Col(s+1).Value=imp(k).Value;
                imp(1).Col(s+1).Cost=imp(k).Cost;
                %..................................
                imp(k)=[]; % delet that imperialist
            end
        end
        %..................................................................
    end
    %show and save results.............................................
%     [ans_cost(it,1),~]=min([imp(1).Col.Cost]);
    [ans_cost(it,1),~]=min([imp.Cost]);
    disp(['Number Of Generatuion ' num2str(it) ', Best Cost = ' num2str(ans_cost(it,1))]);
    mean_cost(it,1)=mean([imp(1).Col.Cost]);
    %..................................................................
```

```
  n_Imp=size(imp,1);
  normilized_probability=[];
end
%% result and plot
[m,p]=min([imp(1).Col.Cost]);
answer=imp(1).Col(p).Value
cost_of_answer=m
figure('Name','Best cost - Generation ','NumberTitle','off');
plot(ans_cost,'LineWidth',2);
ylabel('best cost');
xlabel('Number OF Generation');
```