AN ECONOMICAL MODEL DEVELOPMENT FOR A HYBRID SYSTEM OF GRID CONNECTED SOLAR PV AND ELECTRICAL STORAGE SYSTEM

by

Mohammad Hasan Balali

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ABSTRACT

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Under the Supervision of Professor Hamid Seifoddini
Under the Supervision of Co-Advisor Professor Adel Nasiri

Energy sources management is one of the most important concern in the recent decades. There are finite amount of non-renewable energy sources and one day they will run out if they have been used as primary sources of energy. Renewable energy sources have been significantly reduced the environmental effects. For most of them the source of energy is non-depletable.

One of the concerns associated with renewable resources is uncertainty or unavailability. Energy Storage Systems (ESSs) can help to have more reliable and more efficient systems by adjusting the charge and discharge time and rate. In this study, an economic model is developed for a hybrid system of grid-connected solar photovoltaic, Compressed Air Energy Storage (CAES), and batteries. PV generation depends on irradiance and it is intermittent in nature. CAES can store energy in larger amounts and for longer periods than other storage systems and can offer lower price for stored energy. Batteries are integrated with CAES in this model mainly for lower demand and shorter periods.

The presented model is a non-linear model and it’s been transformed to a linear model in this study. Optimal planning for generation and storage is derived based on the developed model for each day by using operation research techniques to maximize the value of energy which carried over the time. The results are different for each period and are highly dependent on the load demand. The results show that using solar PV panels coupled with energy storage systems increase the efficiency and reliability of the system. In addition to that, efficient use of energy storage system have a great impact on the final prices of electricity since electricity prices in low peak demand periods is lower than high peak periods.

To

My Beloved Family
And My Amazing Wife

TABLE OF CONTENTS

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

CHAPTER FOUR

CHAPTER FIVE

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CAES: Compressed Air Energy Storage

PV$_t$: PV panels generation in period t

SC$_t$: The amount of potential stored electricity in MWh in CAES at the beginning of hour t

SB$_t$: The amount of potential stored electricity in MWh in Batteries at the beginning of hour t

X$_t$: The amount of energy in MWh generated during hour t from the Grid generation facility

Y$_t$: The amount of energy in MWh generated during hour t from the PV generation facility

Δ **SC$_t$**: The difference in stored energy level in CAES from period t to t + 1 in MWh

Δ **SB$_t$**: The difference in stored energy level in Battery from period t to t + 1 in MWh

V$_t$: The value of any stored energy carried over until the hour t in dollar

t$_i$: Hours of the day, $t_i \in \{1, 2, \ldots .., 24\}$

AC$_{(t)}$: Avoided cost of electricity per MWh which is the differences between the cost of electricity on peak time and off peak time in dollar and it depends on finals price of generated electricity in period t.

AC′$_{(t)}$: Avoided cost of PV which is the deference between the cost of electricity from Grid and PV

RC$_{Out}$: Maximum CAES’s generator rate per hour

RC$_{In}$: Maximum CAES’s Compressor rate per hour

RB: Battery’s rate per hour

BC: Battery Capacity at rated depth of discharge

PV: PV Panels Capacity

G: Grid Capacity

C_F: Fuel Cost

f: CAES Conversion Factor

e: Battery Roundtrip Efficiency

D_t: Demand for load during hour t

I: The variable I is an indicator variable equal to one if the subscript condition is satisfied, and zero otherwise.

S: The amount of shortage

S_{max}: Maximum amount of shortage

C_S: Penalty of the shortage

M: Infinite positive number

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CHAPTER ONE

1-Introduction and Problem Definition

The resource’s limitations, technological and environmental restrictions and the high cost of storing energy have invoked researchers from all around the world to focus storing energy more efficiently. The main goal of storing energy is saving energy for future uses when the demands or the prices are higher or when the sources of energy are not available.

During the last decades, renewable energy resources have been widely used to help traditional resources. Traditional resources are going to be depleted if they have been used as primary sources of energy for meeting the demand. Also, the demand for energy grows every year. Environmental impacts of traditional resources are another reason for making renewable energy resources a better option.

Most of the renewable energy resources are not always available; for instance, wind energy is variable and intermittent. The variations in wind speed results in a stochastic output for wind turbines. Therefore, the peak generation of wind farms and peak load demand typically do not occur at the same time [1]. Using the Energy Storage Systems (ESSs) will increase the reliability and efficiency of the system.

Advantages of each ESS can be utilized to achieve specific requirements, optimize the whole system’s performance or improve cycle efficiency [2]. In this study, hybrid generation system consists of Grid, Solar PV Panels, Compressed Air Energy Storage and Batteries. The operational value of storage is determined by comparing the difference in production cost in cases with and without storage systems. When storage systems are added to the generation mix, overall system costs will be minimized because storage is used to displace the operation of the highest cost generators [3].

In this study, part of the generation comes from Solar PV panels. The first issue related to Solar PV panels is the intermittent nature of solar PV generation. The exact amount of generation varies hour to hour or minute to minute and the utility may need to provide voltage regulation services when using solar PV generation in order to smooth out supply and continuously balance electricity supply and load. In addition, an energy utility may need to have backup power available to meet load for periods when solar radiation is lower than expected [4].

Compressed Air Energy Storage (CAES) can store electricity for longer periods of time compared to other electricity storing technologies [5]. In this study, CAES uses energy peak shaving to store the electricity when the prices are lower than peak prices. CAES starts storing with compressing the air, cooling and storing it within underground or aboveground reservoirs. To generate electricity, the air is released, mixed with fuel, ignited, and finally expanded through modified gas turbines to drive generators [5]. Compared with conventional gas turbines, CAES produces more energy while uses the same amount of natural gas.

Batteries are a common type of ESSs, which have been widely used for a long time. There are three main types of conventional storage batteries that are used extensively: the lead–acid batteries, the nickel based batteries and the lithium-based batteries [6]. Researchers from all around the world are still working on development of batteries to increase efficiency and reliability while decreasing the final price of electricity.

One of the key design aspects of any energy storage system, including batteries, is safety, which can be improved by reducing the probability of failure [7]. There is still a need for better understanding of battery response to extreme loading [8]. Battery storage could simply replace CAES for peak shaving or could cover the short time intermittency of PV produced electricity.

The model in this study combines the PV system with CAES and battery storage for peak shaving. Using renewable energy sources coupled with storage systems helps meet the demand with the lowest cost. Wind and solar energy generation sources benefit from energy storage systems as a backup for their intermittent energy generation. Energy storage systems smooth power output and meet demand with adequate stored energy [4]. Figure 1 shows a schematic view of a hybrid system by its components.

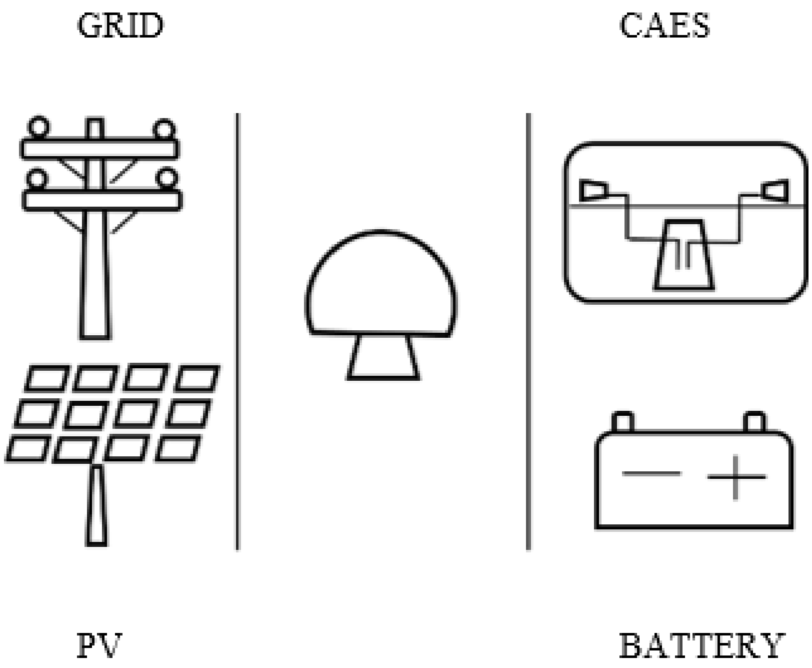


Figure 1: Schematic view of a hybrid system used in this study by its components.

Defining the priority for the components of the system is one of the most important decisions in the hybrid system, and a comparison between the final prices of energy for each component can be done to determine the priority of generation and storage systems to meet demand. Besides the final price of delivered energy, other parameters like periodic major maintenance, life cycle and capital investment can impact the final decision. Table 1 shows capital investment and final price of electricity ($/Kwh) for some types of CAES and Battery.

Table 1: Comparison between final electricity prices and capital investments of different types of CAES and Li-ion battery *[9]*.

System	**Capital Investment**	**Final price $/Kwh**
CAES 50 MW	$60,500,000	1,210
CAES 103 MW	$108,801,225	1,053
CAES 136 MW	$142,401,000	1,050
CAES 183 MW	$174,900,000	957
CAES 322 MW	$247,500,000	769
CAES 441 MW	$289,300,000	656
Li-ion 1000 Kw	$2,551,041	2,551
Li-ion 3000 Kw	$4,164,200	1,388
Li-ion 10000 Kw	$21,834,238	2,183

The electricity price generated from PV is different than the price of electricity which comes from a grid. The price of generated electricity from PV panels is going to decrease. Therefore, without considering the capital investment, it is more affordable to meet demand by PV generation or the amount of stored energy in storage systems and then respond to unmet demand by grid generation [10].

Self-discharging is one of the problems in any electrical network. Self-discharging can occur from generation, transmission, distribution and any steps from generation to delivery. Losses can have great impact on the final price of electricity. Most of the time, electricity self-discharging in the distribution phase are greater than other steps. Overload periods can increase electricity loss due to technical limitations. Finding the exact amount of self-discharging in a system is not always possible due to hidden losses in different systems of a hybrid network. The Top-Down/Bottom-Up method is a common forecasting loss method [11]. Energy Storage Systems lose small amounts of stored energy in each cycle, but compared with Grid, PV and other generation systems self-discharging of ESSs are negligible. On the other hand, ESSs can help the hybrid system to compensate for loss of energy occurring in each phase.

CHAPTER TWO

2- Literature Review

2-1-Energy Sources

Energy sources are one of the most important concern in domestic and international scale. All the announcements about the energy sources have certainly aware every one of the energy problems in the recent decades. One of the most critical concern is the availability of the energy sources. Also, efficient use of resources is rapidly becoming vitally important. Increasing world population leads to requiring increased availability of the energy and more effective ways of utilizing the available portion of the energy sources.

The main efforts of research and development in recent years have been directed towards the development of new alternatives for traditional energy resources or finding more primary sources of energy [12]. There are different kinds of energy sources in the planet earth. Sometimes they are not locally available or predictable. For instance, the solar energy is only usable during the day time when the irradiance of the sun is high enough to generate the expected amount of energy. As same as solar energy, wind power is not always available and using the wind power as an energy generation source needs accurate forecasting. Some other times they are dangerous to be transportable to the other locations. Finding a reliable and safe energy sources is one of the most important concern in recent years.

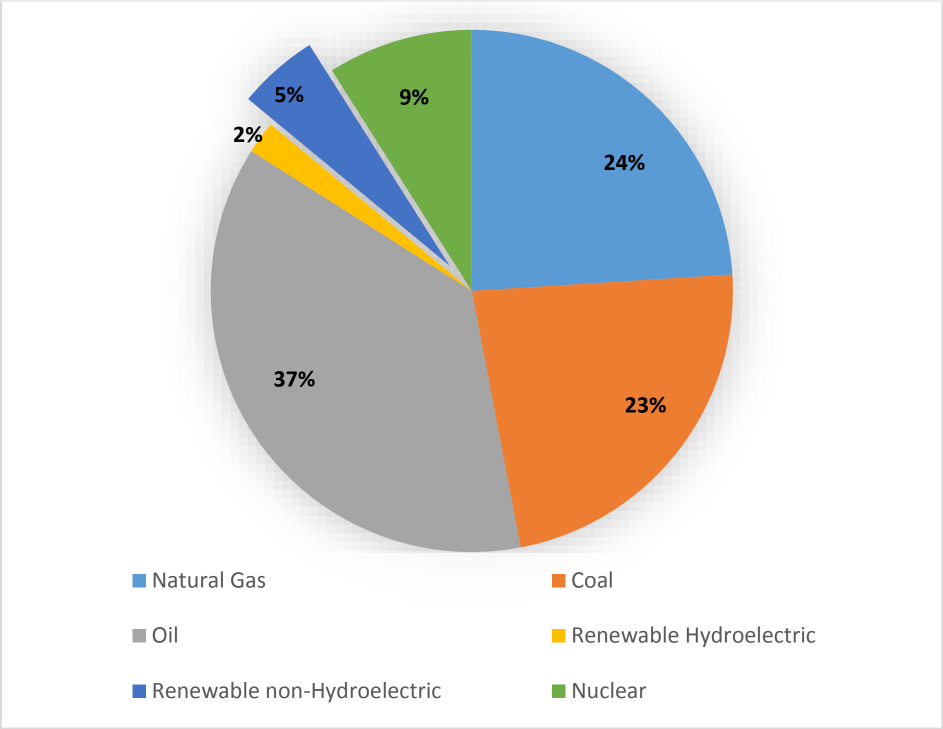


Figure 2: Pie chart depicting the percentage of contributions of energy resources to the total energy consumed in the United State in 2008. Data are from the U.S. Energy Information Administration (2009). [13]

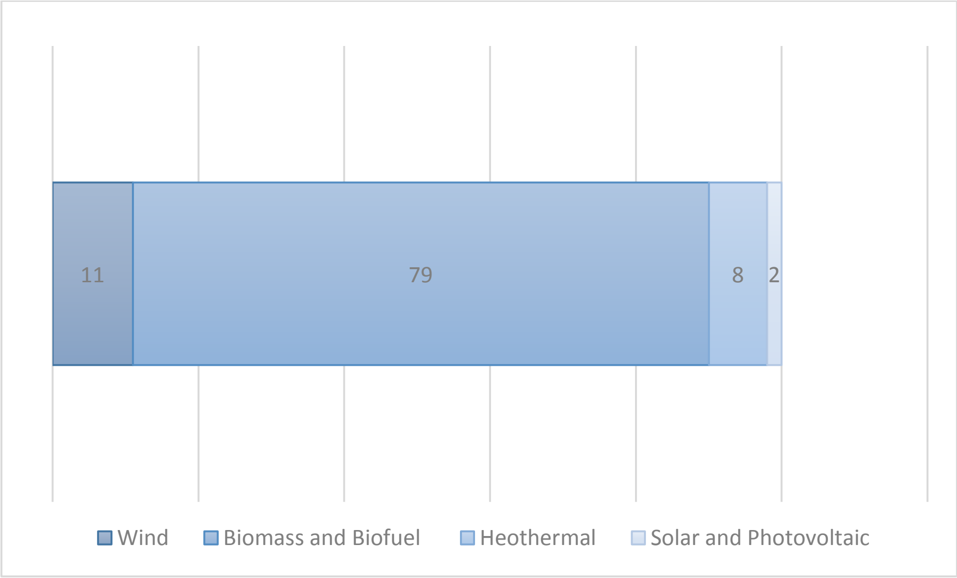


Figure 3: Chart depicting the percentage of contribution of renewable non-hydroelectric energy resources [13]

2-1-1 Non-Renewable Energy Resources

Non renewable energy sources cannot be replenished in a short period of time. There are finite amount of these sources in the earth and one day they will run out if they have been used as primary energy sources. Nonrenewable energy resources generally are energy from fossil fuels which are made of Carbon. Fossil fuels are a valuable source of energy, but the extraction processes are inexpensive compared with other energy sources. They also can easily be stored and shipped to anywhere in the world. Burning fossil fuels leads to several problems for environment like air pollution, water pollution and etc. Natural gas, Petroleum, Coal, Uranium are some examples of nonrenewable energy sources in the world.

2-1-2 Renewable Energy Resources

Renewable energy refers to energy from a source which is continuously replenished by natural processes. State law (Wis. Stat.) defines the following as renewable resources when used to create electricity:

- Wind energy
- Solar thermal energy: using heat from the sun to create electric power
- Photovoltaic energy: a system that directly converts sunlight into electric power
- Biomass: defined as wood or plant material or residue, biological waste
- Geothermal technology
- Hydroelectric with a capacity of less than 60 megawatts
- Tidal or Wave Action

- Fuel Cell: using a renewable fuel as determined by the Commission

The advantages of electric production from renewable resources include:

- Low or no fuel cost (except for some biomass)
- Shorter lead-times for planning and construction as compared to conventional power plants
- Utilize relatively small, modular plant sizes
- Significantly reduced environmental effects compared to fossil fuels
- For many renewable resources, a non-depletable resource base
- Public support for use of renewable resources
- Minimal impacts to the atmosphere
- The water consumed by renewable sources of energy like wind and solar PV is negligible compared with fossil-fuel power plants [14]

The disadvantages of electric production from renewable resources include:

- Public concern for land use, biodiversity, birds and aesthetics in siting a facility
- Relatively high capital cost to construct a renewable facility
- Uneven geographic distribution of renewable resources
- Intermittent availability of some renewable resources for electric production
- Lack of maturity or commercial availability of some technologies

- For some biomass resources, the need to consider environmental implications of the fuel supply [15].

2-1-2-1 Solar Energy

Solar is the sun’s radiation which reach the earth. This energy can be converted to heat and electricity. Solar energy can generate electricity in two ways by using photovoltaic panels or solar thermal methods. Solar energy do not produce CO_2 emission or air pollution and also has the minimum impact on environment when located on the buildings. The generated electricity from solar source is not always constant amount and it highly depends on the irradiance of the sun and it varies hour to hour and day to day. Solar is intermittent in nature and climate conditions and geographical location have a great impact on the amount of generated energy.

2-1-2-1-1 Solar Thermal

Heat from the sun can be used to provide energy in multiple ways. One way is to convert the sunlight into heat using a solar collector. The heat can be used for space heating, water heating, or for another processes. Solar water heaters have been commercially available for many years. The use of solar energy for space heating using “passive” methods has also been popular. Heat from the sun can also be used to heat a fluid that drives a turbine or heat engine to provide energy to a conventional electric generator [15].

2-1-2-1-1 Photovoltaic

Another way to use solar energy is by converting sunlight directly into electricity through the use of photovoltaic cells, which are grouped together to form a panel. Photovoltaic panels can be used in small groups on rooftops or as part of a substantial system for producing large amounts of electrical power. The amount of energy produced by a photovoltaic system depends upon the amount of sunlight available and the size of the system. The intensity of sunlight varies by season of the year, time of day and the degree of cloudiness. As a result of private and government research, photovoltaic systems are expected to become more efficient and affordable in the future. Prices may also decrease as the popularity of photovoltaic systems increases and production increases, producing some economies of scale. Compared to traditional methods of electric generation, photovoltaic systems have few environmental concerns. The primary environmental impact of a large system is visual and can be solved by designing the system to blend with its surroundings [15].

There has been a tremendous development of PV technologies has been realized over the years. The performances of PV technologies just like most other electronic systems are standardized by the International Electrochemical Commission (IEC). [16]

2-1-2-2 Wind Energy

Wind energy is converted to electricity when wind passes by blades mounted on a rotating shaft. As the wind moves the blades, the rotation of the shaft turns a generator which converts the rotational movement into electricity. Three main factors which have impact on the system are the length and design of the blades, the density of the air and wind velocity. Longer blades produce more power output. Cold air is denser than warm air, which means it produces more force, or ability to turn the blades. Also, in general, as elevations increase wind turbines will encounter greater wind velocities [15].

Like other energy resources, using wind energy has several positive and negative effects on environment. One of the major benefits of this technology is that it doesn’t have air pollution and CO_2 emission. Wind energy doesn’t have water consumptions compared with other technologies. Water can be used in initial phases for wind turbines installation and blade washing which is not frequent. Wind energy doesn't produce any waste and byproducts. Also, this technology doesn't have fuel consumption and therefore, natural gas price fluctuation doesn't effect on final price of generated electricity. Final price of electricity is almost low compare to traditional resources. Wind turbines cause several problems for birds and animals which lead to death.

2-1-2-3 Hydropower

The energy from moving water is converted to electricity when water passes by blades similar to those on a ship's propeller. The blades are connected to a rotating shaft which turns a generator to produce electricity [15]. Hydropower is a mature and cost competitive renewable energy source. It plays an important role in today's electricity mix, contributing to more than 16% of electricity generation worldwide and about 85% of global renewable electricity. Furthermore, it helps stabilize fluctuations between demand and supply [17].

Long and productive local generation capability and low life-cycle costs, proven reliability of electricity production with few service interruptions, environmental and socially sustainable development by providing climate change mitigation, flexible operations by enhancing grid stability and enabling use of variable renewables and large-scale energy storage for seasonal load balancing are some benefits of hydropower sources [17].

Hydroelectric power plants produce no air emissions. The barriers created by dams constrain fish and other species to specific pools, impacting their ability to survive and reproduce. The turbines have the potential to damage or kill fish if the fish are not filtered aside on the upstream side of the dam [15].

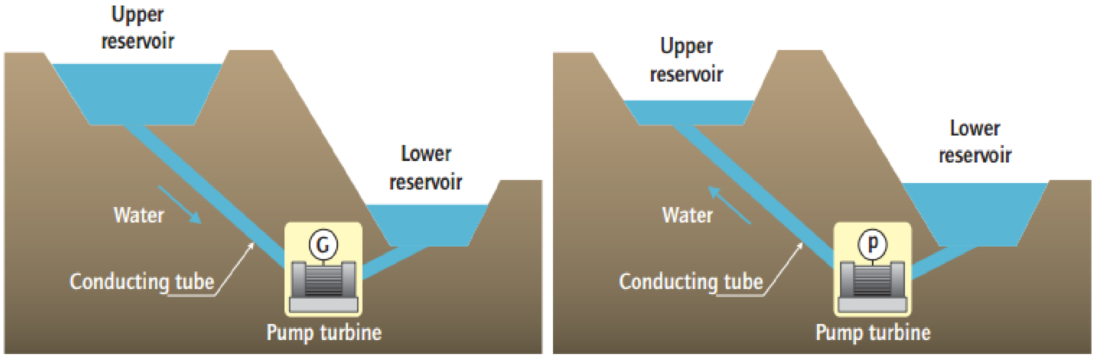


Figure 4: Configuration of a pumped energy storage of hydropower plant. [13]

2-1-2-4 Geothermal

Geothermal energy, earth heat, can be found anywhere in the world. But the high temperature energy that is needed to drive electric generation stations is found in relatively few places [18]. Geothermal energy is the heat from the Earth. It's clean and sustainable. Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface, and down even deeper to the extremely high temperatures of molten rock called magma. Most power plants need steam to generate electricity. The steam rotates a turbine that activates a generator, which produces electricity. Many power plants still use fossil fuels to boil water for steam. Geothermal power plants, however, use steam produced from reservoirs of hot water found a couple of miles or more below the Earth's surface [19].

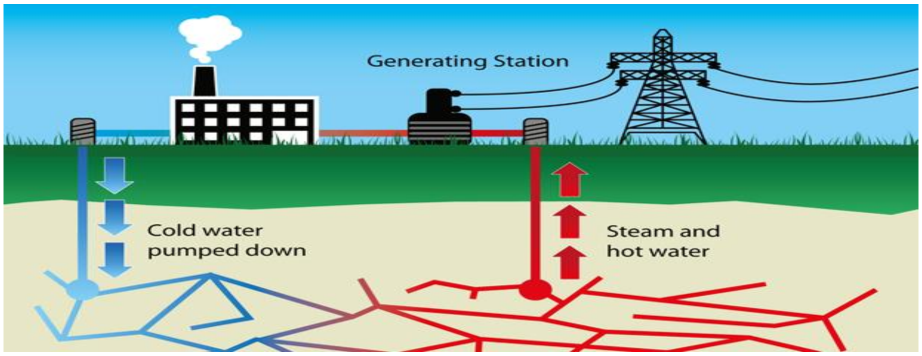


Figure 5: Configuration of a geothermal energy generating station. [16]

2-2- Electrical Storage

Energy storage means absorbing energy, Storing for a period of time and then releasing to the energy suppliers or power services. In this process, energy storage systems (ESSs) can be temporal time bridge or covering a geographical gap between energy supply and demand. Energy storage systems mediate between variable sources and variable loads. Energy storage systems can implement in large or small scale from generation phase to final delivery.

An energy bank deposit must be made at an earlier time for energy to be an available and usable form at the time of high peak demand. Most of the energy storage facilities store energy during low demand and low cost periods and discharged it during high peak demand. Price of energy in high peak demand periods is much higher than low peak demand periods. Therefore, efficient using of energy storage systems can have a great impact on the final price of electricity.

In a very general sense, there are only three purposes for the storage of energy: to make an energy supply portable from essentially non-portable sources, to store from an ongoing source for use at a later time, and to change the ratio of power-to-energy. There are not many attractive choices for storage, and most are not portable or cheap. Batteries are the least obtrusive and the most predictable limited secondary sources, but they are not practical as large-scale primary or secondary sources [12].

Reliability is one the most important parameters in hybrid networks and electricity storage systems will increase the total reliability of the network. Most of the time, electricity shortage is not desirable. ESSs charge when the demand is lower than other period and discharge during high peak demand to smooth the generation system and prevent any shortage in the hybrid system.

Power demand varies from time to time and the prices of electricity change accordingly. The prices for electricity at peak demand periods are higher and at off-peak periods lower. This is caused by differences in the cost of generation in each period. During peak periods when electricity consumption is higher than average, power suppliers must complement the base-load power plants (such as coal-fired) with less cost-effective but more flexible forms of generation, such as oil and gas-fired generators. During the off-peak period when the demand is lower than peak periods, costly types of generation can be stopped. This is a good chance for owners of ESSs to benefit financially. From the utilities' viewpoint there is a huge potential to reduce total generation costs by eliminating the costlier methods, through storage of electricity generated by low-cost power plants [20].

Maintaining a continuous and flexible power supply for consumers is one of the most important characteristics of each electricity generation system. If the proper amount of electricity cannot be provided at the time when consumers need it, the power quality will deteriorate and at worst this may lead to a service interruption. To meet the total amounts of demand appropriate amounts of electricity should be generated continuously, relying on an accurate forecast of the variations in demand [20].

2-2-1 Emerging Needs for ESSs

There are two major market needs for ESSs: to utilize more renewable energy and less fossil fuel, and the future of Smart Grid

2-2-1-1 Utilizing More Renewable Energy Resources

In on-grid areas, the renewable generation may cause several issues in the power grid. First, in power grid operation, the fluctuation in the output of renewable generation makes system frequency control difficult, and if the frequency deviation becomes too wide system operation can deteriorate. Secondly, renewable energy output is undependable since it is relied on weather conditions. Some actions are available to cope with this. Increasing the amount of renewable generation installed which leads to provide overcapacity and another is to spread the installations of renewable generators over a wide area. Installing renewable generators in wide area can take advantage of weather conditions changing from place to place and of smoothing effects expected from the complementarity of wind and solar generators [20].

2-2-1-2 Smart Grid

ESS is expected to play an essential role in the future Smart Grid. ESSs installed in customer side substations can control power flow and mitigate congestion, or maintain voltage in the appropriate range. Another role expected for ESS is for Energy Management Systems (EMS) in homes and residential buildings. With a Home Energy Management System, residential customers will become actively involved in modifying their electricity spending by monitoring their actual consumptions in real time. EMSs in general will need ESS to store electricity from local generation when it is not needed and discharge it when necessary, thus allowing the EMS to function optimally with less power needed from the grid [20].

2-2-2 Electrical Storage Systems Applications

The potential applications for energy storage systems in hybrid network are as follow: [21]

- Energy storage for the producers
- Energy storage for transmission system
- Energy storage for distribution networks
- Energy storage for retailers
- Energy storage for the consumers
- Energy storage for balancing the responsible party (BRP)

In the electrical system the need for maintaining the balance between production and consumption has made the energy storage an issue for long time. The economic conditions for energy storage system, comprising high cost, economic constraints related to access to the grid, insufficient financial return and etc. have prevented the level of development which would have been expected in this area. Every electrical system has its own needs and these lead to the different applications for energy storage.

2-2-2-1 Storage for Producers

The activity of production or generation consist of exploiting power stations to selling the produced energy in a wholesale market. The volume of the energy can be generated depends on the availability of the customers, the power of the system for meeting the demand and the competitiveness of the cost. Demand is not a constant and always fluctuates and it depends on events and especial occasions in a year. Therefore, producers encounter the risk of shortage or over load which both of them have a cost or penalty for producers.

Appropriate management of energy storage can help producers to maximize the revenue associated with energy production. Electricity can be stored when the prices are low and sold later when the prices are higher. The storage devices should be able to store energy for dozen of hours and the capacity should be high enough to enable the system to carried energy from day to night, weekends or weekdays.

2-2-2-2 Storage for Transmission Systems

Depending on the technical characteristics of the power system, energy storage systems can be used in transmission line in order to balance the flow by charging and discharging the storage systems. The main purpose of the power system is generating the energy for customers to respond to the maximum demand at a lowest cost. Transmission system should be reliable and flexible enough to meet customers demand. Every breakdown or shortage in transmission system will lead to energy shortage and inconvenience situations for customers. Therefore, storage systems can balance the transmission system to be more reliable and safer.

2-2-2-3 Storage for Distribution Networks

Energy storage systems had been used for distribution networks for many years. Emergency power is an example of traditional use of storage devices in distribution networks. Distributors may use storage to have smoother loads. Occasionally, demand may increase for a period of time and energy storage systems can be a solution to smooth the demand instead of reinforcement or building a new one.

2-2-2-4 Storage for Retailers

Retailers are associated with selling electricity and providing services to end customers. Retail activities and production activities should be able to supply energy sold to their customers by using their production capacity. Storage management is a method that can manage the risk of price and volume that weigh on the sourcing of retailers.

2-2-2-5-Storage for Consumers

Energy storage is really important for commercial and industrial uses. In some cases, it can have a great impact on residential uses too. The price of energy is not same during a different periods of a day. The prices billed to the customers can show the different prices of electricity in different times of a day. The subscribed power is the maximum value which rarely happens in practice. From customer point of view, it is overpaying for energy needs.

Peak shaving deals with leveling the loads to reduce the subscribed power. In order to implement peak shaving method, storage systems recharge when the customer's load is weak and discharge when customer calls for high power. Customers can also store energy in order to deferral of consumption, quality and continuity of supplying energy.

2-2-3 Classification of Electrical Storage Systems

Electrical storage Systems has been classified into different categories based on the form of energy used. There are five different types of electricity storage systems as mechanical, electrochemical, chemical, electrical and thermal.

Table 2: Classification of electrical storage systems.

Mechanical	Electrochemical	Chemical	Electrical	Thermal
Pumped hydro	Rechargeable battery	Hydrogen	Capacitor	Ice storage air conditioning
Compressed air	Super-Capacitors	Power to gas	Electromagnetic storage	Sensible heat storage
Flywheel	Ultra-Battery	Methane Biofuels		

2-2-3-1 Mechanical Storage Systems

The most common mechanical storage systems are pumped hydroelectric power plants (PHS), compressed air energy storage (CAES) and flywheel energy storage (FES).

2-2-3-1-1 Pumped Hydro

Pumped hydroelectric energy storage is a large, mature, and commercial utility-scale technology currently used at many locations in the United States and around the world [9]. With over 120 GW, pumped hydro storage power plants meet nearly about 3 % of global generation capacity. Conventional pumped hydro storage systems use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging). The first pumped hydro storage plants were used in Italy and Switzerland in the 1890s. Typical discharge times range from several hours to a few days and the efficiency of PHS plants is in the range of 70 % to 85 %. Advantages are the very long lifetime and practically unlimited cycle stability of the installation. Main drawbacks are the dependence on topographical conditions and large land use [20].

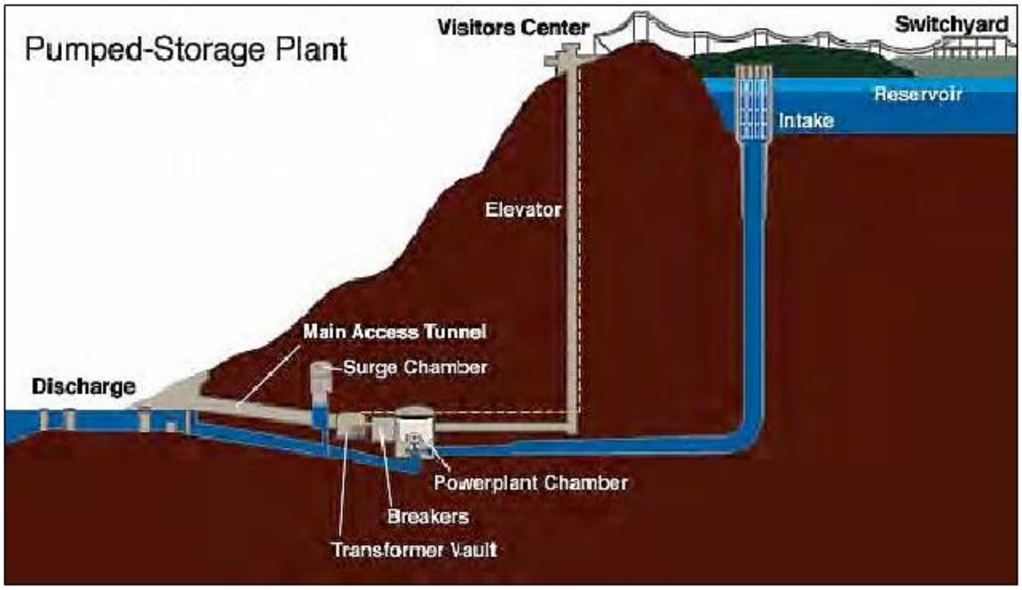


Figure 6: Configuration of a pumped hydro energy storage in a pumped storage plant. [9]

The main limiting factors for PHS appear to be environmental concerns and financial uncertainties rather than the availability of technically feasible sites. PHS developers are proposing innovative ways of addressing the environmental impacts, including the potential use of waste water in PHS applications. Such new opportunities and the increasing need for greater energy storage may lead policymakers to reassess the potential of PHS in the United States, particularly for coupling with intermittent renewable energy sources such as wind and solar power [22].

There are 45 operational pumped hydro station within the United State which can produce up to 26645 Megawatts [23].

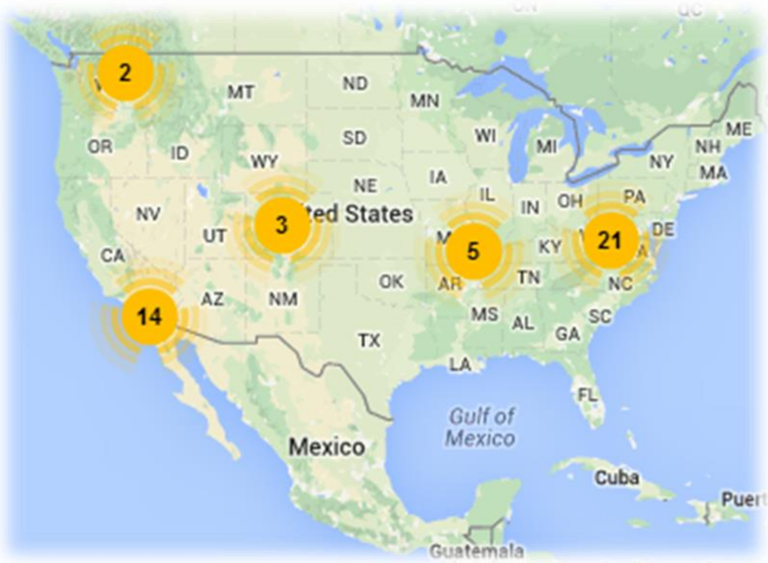


Figure 7: Number of pumped hydro energy storage stations in US, based on data from department of energy (DOE). [23]

2-2-3-1-2 Flywheel

Flywheels store energy in the form of the angular momentum of a spinning mass, called a rotor. The work done to spin the mass is stored in the form of kinetic energy. A flywheel system transfers kinetic energy into ac power through the use of controls and power conversion systems [9].

Flywheel energy storage technology can be used as a substitute for batteries to provide backup power to an uninterruptible power supply (UPS) system. Although the initial cost will usually be higher, flywheels offer a much longer life, reduced maintenance, a smaller footprint, and better reliability compared to a battery. The combination of these characteristics will generally result in a lower life-cycle cost for a flywheel compared to batteries [24].

The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in the speed results in a higher amount of energy stored. To accelerate the flywheel electricity is supplied by a transmission device. If the flywheel’s rotational speed is reduced electricity may be extracted from the system by the same transmission device [20].

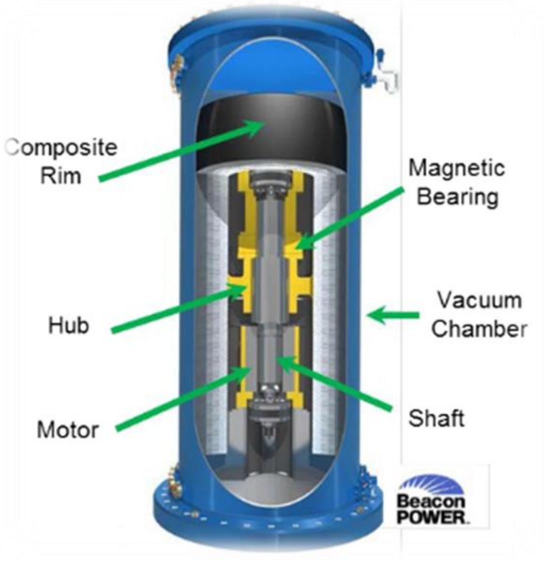


Figure 8: Configuration of a flywheel energy storage system. *[9]*

Currently, there are 32 operational flywheel project within the United State of America which can produce energy up to 98 Megawatts [23].

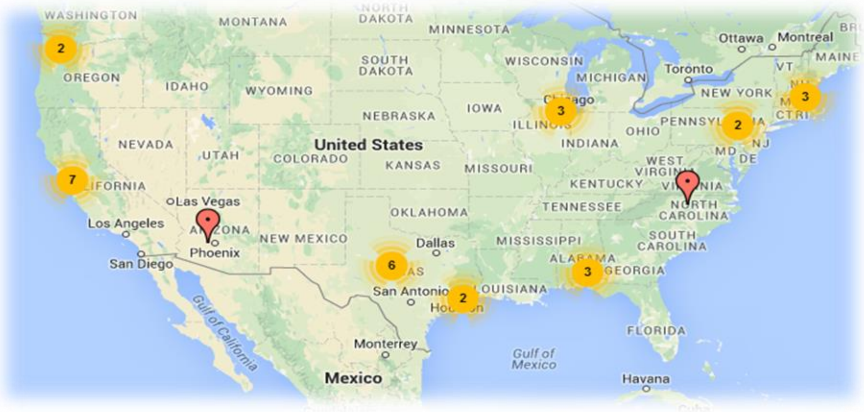


Figure 9: Number of flywheel energy storage stations in US, based on data from department of energy (DOE). [23]

2-2-3-1-3 Compressed Air Energy Storage

CAES systems use off-peak electricity to compress air and store it in a reservoir, either an underground cavern or aboveground pipes or vessels. When electricity is needed, the compressed air is heated, expanded, and directed through an expander or conventional turbine-generator to produce electricity [9].

Compressed air energy storage is a technology known and used since the 19th century for different industrial applications. Air is used as storage medium due to its availability. Electricity is used to compress air and store it in either an underground structure or an above-ground system of vessels or pipes. When needed the compressed air is mixed with natural gas, burned and expanded in a modified gas turbine. Typical underground storage options are caverns, aquifers or abandoned mines. The advantage of CAES is its large capacity; disadvantages are low round-trip efficiency and geographic limitation of locations [20].

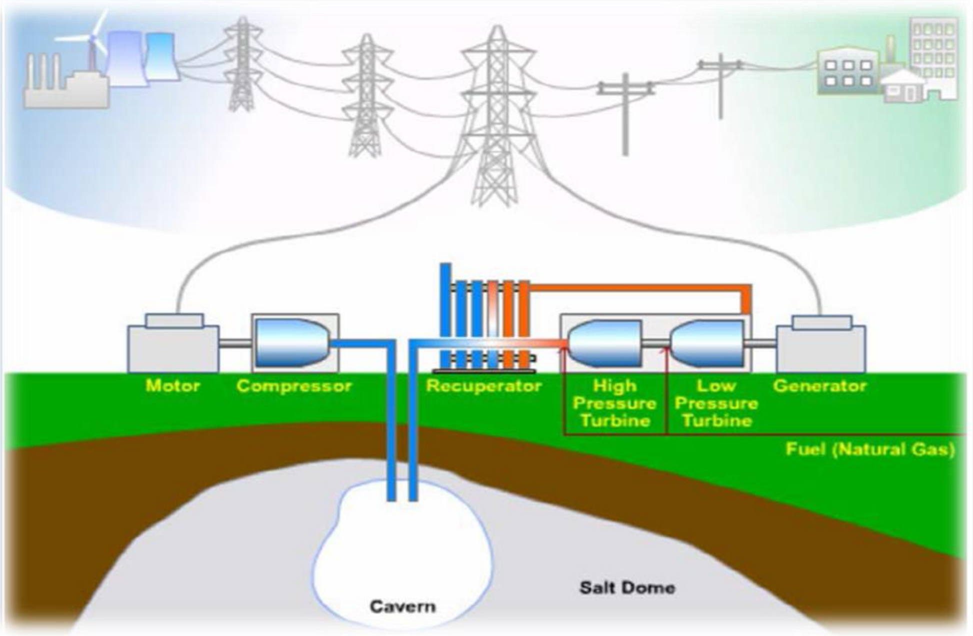


Figure 10: Schematic of a Compressed Air Energy Storage power plant with underground reservoir. [9]

One of the most important feature of CAES is its discharge time which is in tens of hours correspondingly to high size of 1000 MW. There are two operating first generation system one in Germany and one in Alabama in the US. CAES plant has been operating in the Germany, since December 1978, demonstrating strong performance with 90-percent availability and 99-percent starting reliability. In the recent years, researchers tried to find a better way for implementing second generation of CAES with lower installation cost, high efficiency and faster construction time [9].

Most of the time, CAES plants using aboveground air are smaller than those using underground storage. Capacity goes down between 3 to 50 MW and discharge time increases between 2 to 6 hours. Aboveground plants are more expensive but are easier to site. Underground CAES storage plants are more cost effective due to their capacity up to 400 MW and discharge time between 8 to 26 hours [9].

Currently, there are 8 operational compressed air stations within the United State of America which can produce up to 780 Megawatts.

Figure 11: Number of compressed air energy storage stations in US, based on data from department of energy (DOE). [23]

Compare to other electricity storage systems CAES can store the electricity for longer periods of time. The final price of generated electricity is lower than other storage systems. The large capacity of CAES is another advantage of this storage system. CAES can be coupled with lower capacity storage systems to increase the total efficiency of the hybrid system.

2-2-3-2 Electrochemical Storage System

Battery is the simplest example of a storage system which comes to mind. There are different types of rechargeable batteries and most of them are mature for practice use. In this study, some types of batteries will be discussed. Many different types of advanced materials for batteries are now available, some of which possess functional properties [25]. Some of these advanced materials are the solution to help the environment and reduce energy dissipation for strategies toward sustainability and energy efficiency [26].

2-2-3-2-1 Lead Acid Battery

Lead acid batteries are the oldest form of rechargeable batteries which have been used since mid-1800. Lead acid batteries can be used in both mobile and stationary application in each phase of generation to final delivery. Typical applications of lead acid batteries are emergency power supply systems, stand-alone systems with PV, battery systems for mitigation of output fluctuations from wind power and as starter batteries in vehicles. In the past, batteries mostly had been used as storage systems in grids.

Compare with mobile batteries, stationary batteries should have better quality and reliability. Cost of stationary batteries are far higher than starter batteries but mass production of stationary batteries will lead to price reduction. One disadvantage of lead acid batteries is usable capacity decrease when high power is discharged. For example, if a battery is discharged in one hour, only about 50 % to 70 % of the rated capacity is available. Other drawbacks are lower energy density and the use of lead, a hazardous material prohibited or restricted in various jurisdictions. Advantages are a favorable cost/performance ratio, easy recyclability and a simple charging technology [20].

All lead acid batteries share a common chemistry that positive electrode is composed of lead-dioxide, pbO_2 and negative electrode is composed of metallic lead, pb. The electrolyte is sulfuric acid solution. Lead acid energy storage are divided in two categories, lead acid carbon technologies and advanced lead acid technologies.

One of the most important characteristics of carbon lead acid batteries is the high rate in both charging and discharging. High current rate is available with Nickel-Metal-Hybrid (Ni-MH) and Li-ion batteries [27].

Currently, there are 40 operational lead acid battery projects within the United State of America which can produce energy up to 132 Megawatts.

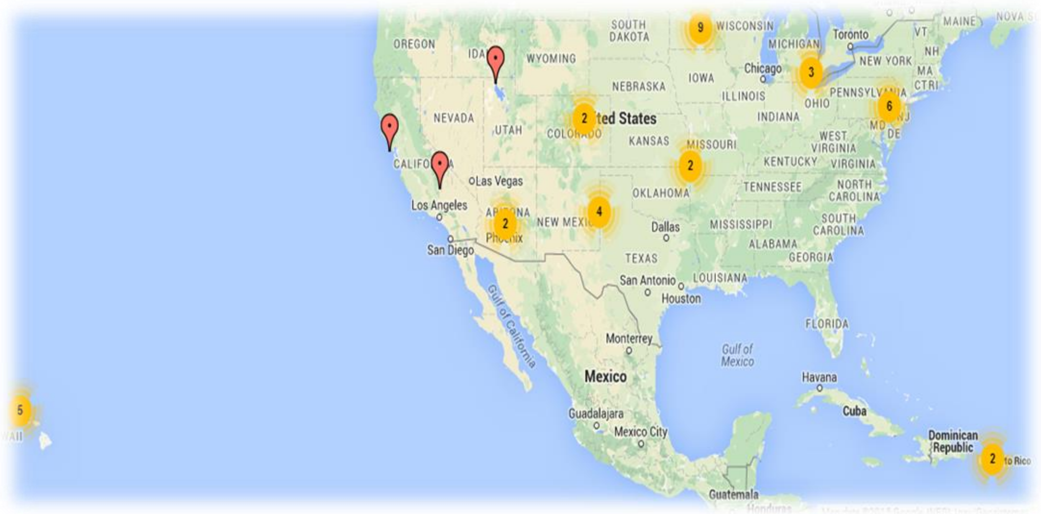


Figure 12: Number of lead acid battery energy storage stations in US, based on data from department of energy (DOE). [23]

2-2-3-2-2 Lithium Ion Battery

Lithium ion batteries have become the most important storage technology in the areas of portable and mobile applications (e.g. laptop, cell phone, electric bicycle and electric car). High cell voltage levels of up to 3.7 nominal Volts means one lithium ion cell can replace three Ni-Cd cells which have a cell voltage of only 1.2 Volts. Lithium ion batteries generally have a very high efficiency compared with other batteries, typically in the range of 95 % - 98 %. Discharge time can be from seconds to weeks which makes them a very flexible and universal storage technology. Standard cells with 5000 full cycles can be obtained on the market at short notice, but even higher cycle rates are possible after further development, mainly depending on the materials used for the electrodes. Since lithium ion batteries are currently still expensive, they can only compete with lead acid batteries in those applications which require short discharge times. Lithium ion battery technology is still developing, and there is considerable potential for further progress [20].

The impressive scale of Li-ion battery production is driving a trend in cost reduction and performance improvements that make this technology attractive for grid storage applications in the near term. The technology advancements and scale that have made Li-ion systems viable for consumer portable electronics has driven favorable energy density, safety, and cost. Li-ion systems designated to satisfy PV Grid Integration applications are primarily employed to smooth PV power and voltage impacts for durations of seconds to minutes. They may be sited at utility-scale PV generation sites or on feeders that are affected by high penetrations of distributed rooftop [28].

Common types of liquid Li-ion batteries are cylindrical or prismatic. Prismatic polymer Li-ion batteries are usually used in the small portable devices like MP3 players and Notebooks. There are many different Li-ion chemistries. Figure 9 shows a schematic views of prismatic and cylindrical Li-Ion battery.

A Li-ion battery cell contains two reactive materials capable of undergoing an electron transfer chemical reaction. To undergo the reaction, the materials must contact each other electrically, either directly or through a wire, and must be capable of exchanging charged ions to maintain overall charge neutrality as electrons are transferred [9]. Figure 10 shows a schematic principles of a Li-Ion Battery.

The large manufacturing scale of Li-ion batteries estimated to be 30 GWh by 2015 which can result in lower cost for battery packs which can also use for grid supporting system which need less than 4 hours of storage. The life cycle estimates 365 cycle annually for 15 years [9].

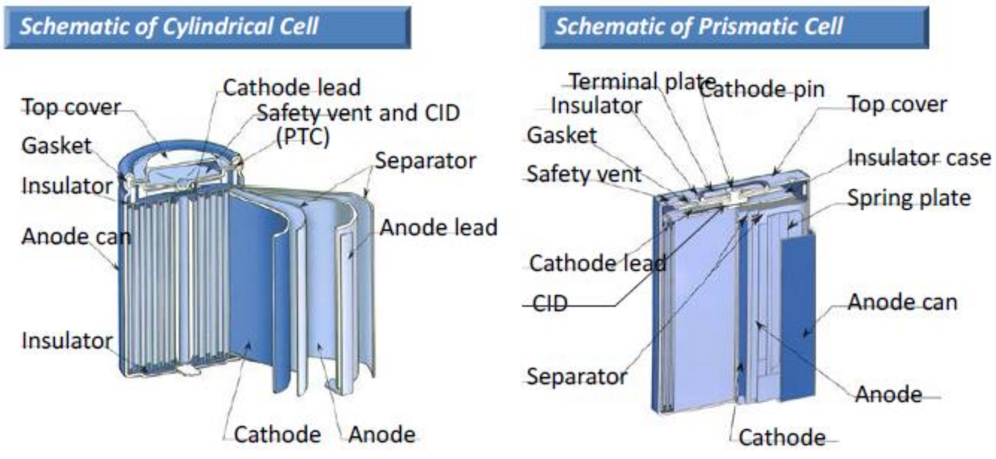
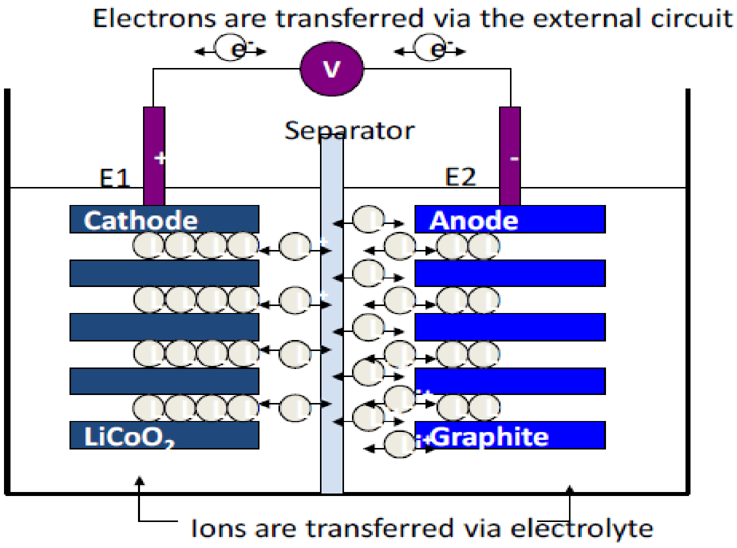


Figure 13: Schematic views of prismatic and cylindrical Li-Ion battery. [9]



- Chemical reactions involve exchanges of charge between chemical species
- In electrochemical reactions, electric current (charge) is carried by the flow of electrons in the external circuit and by the flow of ions in the electrolyte.
- The flow of ions must be equal to the flow of electrons to maintain local charge balance.

Figure 14: Configuration of a Lithium-Ion battery energy storage. [9]

Currently, there are 186 operational Lithium-Ion battery projects within the United State of America which can produce energy up to 314 Megawatts.

Figure 15: Number of Li-ion battery energy storage stations in US, based on data from department of energy (DOE). [23]

2-2-3-2-3 Zinc Bromine Battery

Zinc Bromine battery is a kind of flow battery which Zink is solid during charging time and dissolved when discharged. The Bromine is always dissolve in aqueous electrolyte. Each cell is composed of two electrode surfaces and two electrolyte flow streams separated by a micro-porous film. The positive electrolyte is called a catholyte; the negative is the anolyte. Both electrolytes are aqueous solutions of zinc bromine ($ZnBr_2$). During charge, elemental Zinc is platted onto the negative electrode and elemental bromine is formed at the positive electrode. Ideally, this elemental bromine remains only in the positive electrolyte. The micro-porous separator allows zinc ions and bromine ions to migrate to the opposite electrolyte flow stream for charge equalization at the same time, it inhibits elemental bromine from crossing over from the positive to the negative electrolyte, reducing self-discharge because of direct reaction of bromine with zinc [9].

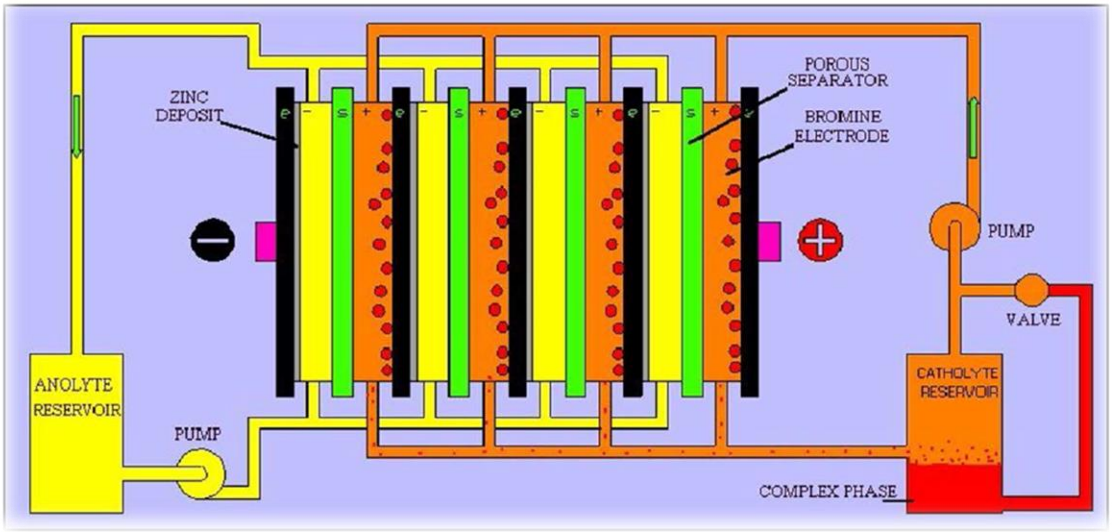


Figure 16: Schematic view of a Zinc-Bromine battery configuration. *[9]*

The life time for Zink-Bromine batteries is about 20 years and approximate AC to AC efficiency is 65 percent [23].

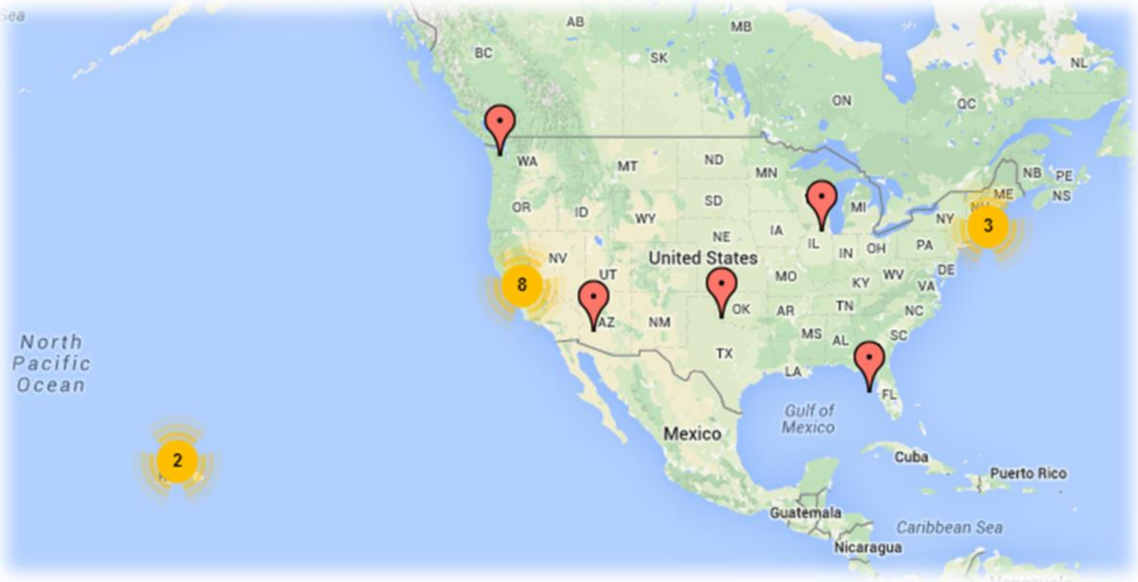


Figure 17: Number of Zinc-Bromine battery energy storage stations in US, based on data from department of energy (DOE). [23]

2-2-3-3 Chemical Electricity Storage Systems

Chemical energy storage system mostly focus on hydrogen and synthetic natural gas (SNG), since these could have a significant impact on the storage of electrical energy in large quantities. The main purpose of such a chemical energy storage system is to use “excess” electricity to produce hydrogen via water electrolysis. Once hydrogen is produced different ways are available for using it as an energy carrier, either as pure hydrogen or as SNG. Although the overall efficiency of hydrogen and SNG is low compared to storage technologies such as Li-ion, chemical energy storage is the only concept which allows storage of large amounts of energy, up to the TWh range, and for greater periods of time, even as seasonal storage. Another advantage of hydrogen and SNG is that these universal energy carriers can be used in different sectors, such as transport, mobility, heating and the chemical industry [20].

2-2-3-3-1 Hydrogen Storage Systems

A typical hydrogen storage system consists of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is an electrochemical converter which splits water with the help of electricity into hydrogen and oxygen. heat is required during the reaction. Hydrogen is stored under pressure in gas bottles or tanks, and this can be done practically for an unlimited time. To generate electricity, both gases flow into the fuel cell where an electrochemical reaction which is the reverse of water splitting takes place: hydrogen and oxygen react and produce water, heat is released and electricity is generated. For economic and practical reasons oxygen is not stored but vented to the atmosphere on electrolysis, and oxygen from the air is taken for the power generation. In addition to fuel cells, gas motors, gas turbines and combined cycles of gas and steam turbines are in discussion for power generation. Different approaches exist to storing the hydrogen, either as a gas under high pressure, a liquid at very low temperature, adsorbed on metal hydrides or chemically bonded in complex hydrides. However, for stationary applications gaseous storage under high pressure is the most popular choice. Up to now there have not been any commercial hydrogen storage systems used for renewable energies [20].

During off-peak hours, electrolyzers could use energy from the wind turbines or the grid to generate hydrogen and store it in turbine towers. The stored hydrogen could later be used to generate power via a fuel cell during times of peak demand. This capacity for energy storage could significantly mitigate the drawbacks to wind’s intermittent nature and provide a cost-effective means of meeting peak demand. Hydrogen storage creates a number of additional considerations in turbine tower design. Under certain conditions hydrogen tends to react with steel, adversely affecting the mechanical properties such as ductility, yield strength, and fatigue life. Additionally, storing hydrogen at pressure significantly increases the stresses on the tower. These factors require a structural analysis to evaluate how internal pressure may affect the tower’s design life. Hydrogen storage creates a number of additional considerations in turbine tower design. Under certain conditions hydrogen tends to react with steel, adversely affecting the mechanical properties such as ductility, yield strength, and fatigue life [29].

2-2-3-3-2 Synthetic Natural Gas (SNG)

Synthesis of methane is the second option to store electricity as chemical energy. Here a second step is required beyond the water splitting process in an electrolyzer, a step in which hydrogen and carbon dioxide react to methane in a methanation reactor. As is the case for hydrogen, the SNG produced can be stored in pressure tanks, underground, or fed directly into the gas grid. Several CO2 sources are conceivable for the methanation process, such as fossil-fuelled power stations, industrial installations or biogas plants. To minimize losses in energy, transport of the gases CO2 (from the CO2 source) and H2 (from the electrolysis plant) to the methanation plant should be avoided. The production of SNG is preferable at locations where CO2 and excess electricity are both available. In particular, the use of CO2 from biogas production processes is promising as it is a widely-used technology. Nevertheless, intermediate on-site storage of the gases is required, as the methanation is a constantly running process. The main disadvantage of SNG is the relatively low efficiency due to the conversion losses in electrolysis, methanation, storage, transport and the subsequent power generation. The overall AC-AC efficiency, < 35 %, is even lower than with hydrogen [20].

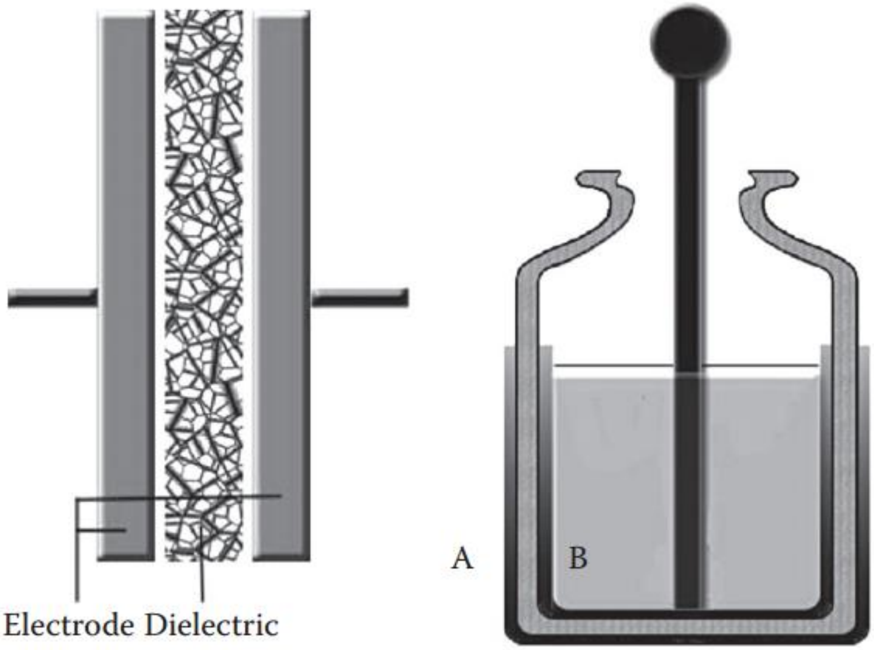
2-2-3-4 Electrical Storage Systems

2-2-3-4-1 Super Capacitor Systems

Both batteries and supercapacitors show great potential as electrical energy storage devices. Although batteries show higher energy densities, they have lower power handling abilities and shorter cycle lives [30]. Since the 1980s, electrochemical double-layer capacitors (EDLCs or supercapacitors) have been developed to meet this demand, due to their extremely rapid rates of charge and discharge and their essentially unlimited cycle life [31].

The storage of electrical energy in supercapacitors relies on the formation of an electric double layer at the interface between a solid electrode and a liquid electrolyte solution. Upon charging, energy is stored as the cations and anions are electrostatically attracted to different electrodes, forming the double layers. Among all potential materials for supercapacitors, carbon has been widely used as the electrode, because of its high porosity, good electronic conductivity, and low cost [32].

An electric capacitor has a sandwich structure containing two conductive plates (normally made of metal) surrounding a dielectric or insulator. An external voltage difference is applied across the two plates, creating a charging process. During charging, the positive charges gradually accumulate on one plate (positive electrode) while the negative charges accumulate on the other plate (negative electrode). When the external voltage difference is removed, both the positive and negative charges remain at their corresponding electrodes. In this way, the capacitor plays a role in separating electrical charges. The voltage difference between the two electrodes is called the cell voltage of the capacitor. If these electrodes are connected using a conductive wire with or without a load, a discharging process occurs the positive and negative charges will gradually combine through the wire [33].



(a) (b)

Figure 18: Simplified schematic of a capacitor design. [33]

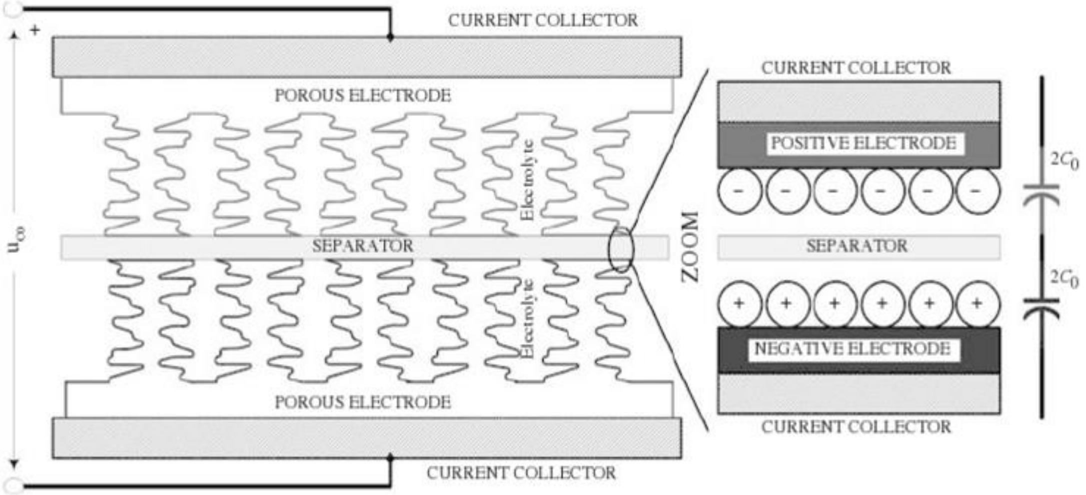


Figure 19: Construction of the electrochemical double layer ultra-capacitor with porous electrodes (activated carbon). [34]

2-2-3-4-1 Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage (SMES) systems work according to an electrodynamic principle. The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature. Today materials are available which can function at around 100 °K. The main component of this storage system is a coil made of superconducting material. Additional components include power conditioning equipment and a cryogenically cooled refrigeration system [20].

The main advantage of SMES is the very quick response time. The requested power is available almost instantaneously. Moreover the system is characterized by its high overall round-trip efficiency (85 % - 90 %) and the very high power output which can be provided for a short period of time. There are no moving parts in the main portion of SMES, but the overall reliability depends crucially on the refrigeration system. In principle the energy can be stored indefinitely as long as the cooling system is operational, but longer storage times are limited by the energy demand of the refrigeration system. Large SMES systems with more than 10 MW power are mainly used in particle detectors for high-energy physics experiments [20].

2-2-3-5 Thermal Storage Systems

Thermal energy storage (TES) systems can store heat or cold to be used later under varying conditions such as temperature, place or power. An active storage system is characterized by forced convection heat transfer into the storage material. The storage material circulates through a heat exchanger, a solar receiver or a steam generator. The benefits that can be obtained when implementing storage in an energy system are better economics by reducing capital and operational costs, better efficiency by achieving a more efficient use of energy, less pollution of the environment and less CO2 emissions and better system performance and reliability [35].

There are mainly two types of TES systems, that is, sensible (e.g., water and rock) and latent (e.g., water/ice and salt hydrates). For each storage medium, there is a wide variety of choices depending on the temperature range and application. TES deals with the storing of energy, usually by cooling, heating, melting, solidifying, or vaporizing a substance, and the energy becomes available as heat when the process is reversed. The selection of a TES is mainly dependent on the storage period required, that is, diurnal or seasonal, economic viability, operating conditions, and so on [36].

CHAPTER THREE

3-Optimization of Non-Linear Systems

3-1 Operation Research

The main origin of Operation Research (O.R.) was during World War II when Britain was having very limited resources, therefore there was an urgent need to allocate resources to the various operations and activities. Nowadays, the impact of OR can be seen in many areas. A large number of management consulting firms are currently engaged in OR activities in areas such as transportation, libraries, hospitals, city planning and financial institution. There are several definitions of OR. For instance, “OR is a scientific method of providing executive departments with a quantitative basis for decisions regarding the operations under their control”, Morse and Kimbel (1946). Different phases of OR are as follow [37]:

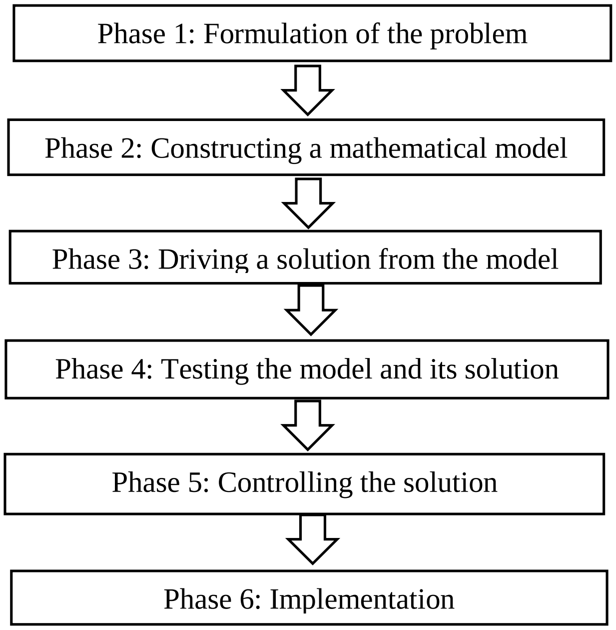


Figure 20: Operation Research phases. [37]

3-1-1 Formulation of Problem

To find the solution of an OR model, problem should be formulated using the appropriate model. The following information is needed for problem formulation [37].

1) Decision Makers
2) Objective Function
3) Controllable Variables
4) Uncontrollable Variables
5) Restrictions and Constraints

3-1-2 Constructing a mathematical model

In this phase, problems should using an appropriate model to be more convenient for further analysis. A mathematical model should be able to represent the system under study in all aspects. A mathematical model consists of objective function, decision variables and constraints.

3-1-3 Deriving a solution from the model

By using OR techniques and methods, a solution for the mathematical model should be found. In OR models, it’s always desirable to find the optimal solution. Optimal solution in the one that maximize or minimize the objective function.

3-1-4 Testing the model and its solution

After getting the solution, it is necessary to test the solution for errors. There is more to testing the solution that just making a comparison between the problem and the original model which helps to reveal any mistake.

3-1-5 Controlling the solution

The model requires immediate modification as soon as one or more of the variables change. As the conditions are constantly changing in the real world, the model and optimal solution may not remain valid for throughout the time horizon and should thus be updated continuously.

3-1-6 Implementation

This is the final phase of each OR model. As changes to the variables occur, the model and solution should be updated immediately.

3-2 Operation Research Techniques and Tools

Operations Research (O.R.) is a discipline that deals with the application of advanced analytical methods to help make better decisions [38]. The terms management science and analytics are sometimes used as synonyms for operations research. Employing techniques from other sciences like mathematical sciences, such as mathematical modeling, statistical analysis, and mathematical optimization, operations research arrives at optimal or near-optimal solutions to complex decision-making problems.

Operations research overlaps with other disciplines, notably industrial engineering and operations management. It is often concerned with determining a maximum (such as profit, performance) or minimum (such as loss, risk, or cost.)

Operations research involves a wide range of problem-solving techniques and methods to improve decision-making and efficiency, such as simulation, mathematical optimization, queuing theory, Markov decision processes, economic methods, data analysis, statistics, neural networks, expert systems, and decision analysis. Nearly all of these techniques involve the construction of mathematical models that attempt to describe the system.

Because of the computational and statistical nature of most of these fields, O.R. also has strong ties to computer science. Operations researchers faced with a new problem must determine which of these techniques are most appropriate given the nature of the system, the goals for improvement, and constraints on time and computing power [39].

Operation research gives stress on the analysis of operations as a whole. It uses several tools and techniques available from the field of mathematics, statistics, cost analysis or numerical calculation. Some such techniques are linear programming, non-linear programming, integer programming, dynamic programming, goal programming, game theory, inventory control, PERT-CPM and simulation.

3-2-1 Linear Programming

The term Linear Programming (LP) is the combination of the two terms. “Linear” means that all the relations in the problem are linear and “Programming” refers to the process determining particular program. The linear programming method is a technique of choosing the best alternative from the set of feasible alternatives while objective functions and constraints can be expressed as linear mathematical function. The linear function that is going to be optimized is the objective function and the conditions of the problems are constraints. Linear programming is a widely used in field of optimization since many practical problems in operations research can be expressed as linear programming problems. A general linear problem can be stated as follows [37]:

Find X_1, $X_{2,}$ …Xn which optimize the linear function.

$$Z = C_1X_1 + C_2X_2 + \ldots\ldots\ldots + C_nX_n$$

Subject to the constraints:

$$A_{11}X_1 + A_{12}X_2 + \ldots\ldots + A_{1n}X_n\ (<=>)\ b_1$$

$$A_{21}X_1 + A_{22}X_2 + \ldots\ldots + A_{2n}X_n\ (<=>)\ b_2$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$A_{m1}X_1 + Am_2X_2 + \ldots\ldots + A_{mn}X_n\ (<=>)\ b_n$$

$$X_i > 0$$

The problem of solving a system of linear inequalities dates back at least as far as Fourier, who in 1827 published a method for solving them [40]. The first linear programming formulation of a problem that is equivalent to the general linear programming problem was given by Leonid Kantorovich in 1939, who also proposed a method for solving it. He developed the LP problem during World War II as a way to plan expenditures and returns so as to reduce costs to the army and increase losses incurred by the enemy [41].

The main advantages of linear programming are as follows [37]:

- It indicates how the available resources can be used in the best way to optimize the objective function.
- It helps in attaining the optimum use of the productive resources and manpower.
- It improves the quality of decisions.
- It also reflects the drawbacks of the production process.

- It helps in re-evaluation of a basic plan with changing conditions.

3-2-2 Non-Linear Programming

Minimize f(x)

S.t. $g_i(x) \leq 0$ for i=1,…..,m

$h_i(x) = 0$ for i=1,……,l

$x \in X$

Where f, g_1,..., g_m, h_1, …., h_l, are functions defined on R^n, X is a subset of R^n, and x is a vector of n components x_1, ..., x_n. The above problem must be solved for the values of the variables x_l,.., x_n that satisfy the restrictions and meanwhile minimize the function f [42].

In general, the main difference between nonlinear programming and linear programming is that nonlinear programming consist of at least one nonlinear function which could be the objective function, one or more constraints. Most of the systems in real world are inherently nonlinear. The problem is that nonlinear models are much more difficult to optimize. There are several reasons as follows:

- It's hard to distinguish a local optimum from a global optimum point

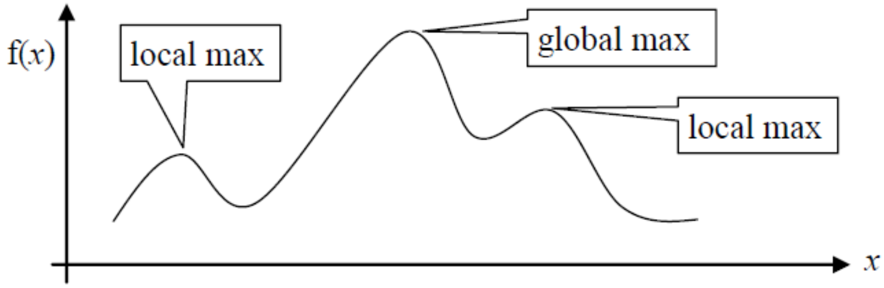


Figure 21: Local optimum points versus global optimum points of a feasible region for a non-linear problem. [32]

- There may be multiple disconnected feasible regions
- Different starting points may lead to different final solution
- It may be difficult to find a feasible starting point
- It’s difficult to keep satisfy equality constraints
- Different algorithms and solvers arrive at different solutions

3-2-3 Simplex Methods

The basic computational step in the simplex algorithm is the same as that in most of elementary linear algebra. This is the operation on matrices used to solve systems of linear equations [43]. The simplex method is a method for solving problems in linear programming. This method, invented by George Dantzig in 1947.

3-2-3-1 Basic steps of the simplex algorithm

- Step 1: Write the linear programming problem in standard form

Turning a problem into standard form involves the following steps.

1) Turn Maximization into minimization and write inequalities in standard order. This step is obvious. Multiply expressions, where appropriate, by -1.

2) Introduce slack variables to turn inequality constraints into equality constraints with nonnegative unknowns. Any inequality of the form $a_1 x_1 + \cdot \cdot \cdot + a_n x_n \leq c$ can be replaced by $a_1 x_1 + \cdot \cdot \cdot + a_n x_n + s = c$ with $s \geq 0$.

3) Replace variables which are not sign-constrained by differences. Any real number x can be written as the difference of nonnegative numbers $x = u - v$ with $u, v \geq 0$.

- Step 2: Write the coefficients of the problem into a simplex tableau

The coefficients of the linear system are collected in an augmented matrix as known from Gaussian elimination for systems of linear equations; the coefficients of the objective function are written in a separate bottom row with a zero in the right hand column. In the following steps, the variables will be divided into m basic variables and n − m non-basic variables. We will act on the tableau by the rules of Gaussian elimination.

- Step 3: Gaussian elimination

For a given set of basic variables, we use Gaussian elimination to reduce the corresponding columns to a permutation of the identity matrix. This amounts to solving Ax = b in such a way that the values of the non-basic variables are zero and the values for the basic variables are explicitly given by the entries in the right hand column of the fully reduced matrix. In addition, we eliminate the coefficients of the objective function below each pivot. The solution expressed by the tableau is only admissible if all basic variables are non-negative. At later stages in the process, the selection rules for the basic variables will guarantee that an initially feasible tableau will remain feasible throughout the process.

- Step 4: Choose new basic variables

If, at this stage, the objective function row has at least one negative entry, the cost can be lowered by making the corresponding variable basic. This new basic variable is called the entering variable. Correspondingly, one formerly basic variable has then to become non-basic, this variable is called the leaving variable.

(i) The entering variable shall correspond to the column which has the most negative entry in the cost function row. If all cost function coefficients are non-negative, the cost cannot be lowered and we have reached an optimum. The algorithm then terminates.

(ii) Once the entering variable is determined, the leaving variable shall be chosen as follows. Compute for each row the ratio of its right hand coefficient to the corresponding coefficient in the entering variable column. Select the row with the smallest finite positive ratio. The leaving variable is then determined by the column which currently owns the pivot in this row. If all coefficients in the entering variable column are non-positive, the cost can be lowered indefinitely, i.e., the linear programming problem does not have a finite solution. The algorithm then also terminates.

(iii) Choosing the right entering variable can guarantee that the objective function will not be worsen in each iterate.

If entering and leaving variable can be found, go to Step 3 and iterate.

- Step 5: Read off the solution

The solution represented by the final tableau has all non-basic variables set to zero, while the values for the basic variables can be can be read off the right hand column. The bottom right corner gives the negative of the objective function.

3-2-3-2 Numerical Example of Simplex Method

Suppose that this linear problem is solved by using Simplex method.

Max $Z = 3x_1 + 5x_2$

S.t. $x_1 \leq 4$

$2x_2 \leq 12$

$3x_1 + 2x_2 \leq 18$

$x_1 , x_2 \geq 0$

First, LP should be re-written in the standard form as follows:

$$\text{Min } -Z = -3x_1 - 5x_2$$

S.t.

$$x_1 + S_1 = 4$$

$$2x_2 + S_2 = 12$$

$$3x_1 + 2x_2 + S_3 = 18$$

$$x_1 , x_2 \geq 0$$

Table 3: Numerical example of simplex method, iteration 1.

	X_1	**X_2**	**S_1**	**S_2**	**S_3**	**RHS**
S_1	1	0	1	0	0	4
S_2	1	2	0	1	0	12
S_3	3	2	0	0	1	18
Z	-3	-5	0	0	0	0

In the first iteration, x_2 has been selected as entering variable and S_2 has to leave the basic solution since Min {4/0, 12/2, and 18/2} is 12/2 which is related to S_2.

Table 4: Numerical example of simplex method, iteration 2.

	X_1	**X_2**	**S_1**	**S_2**	**S_3**	**RHS**
S_1	1	0	1	0	0	4
X_2	0	1	0	1/2	0	6
S_3	3	0	0	-1	1	6
Z	-3	0	0	5/2	0	30

In the second iteration, x_1 has been selected as entering variable and S3 has to leave the basic solution since Min {4/1, 6/0, and 6/3} is 6/3 which is related to S3.

Table 5: Numerical example of simplex method, iteration 3.

	X_1	X_2	S_1	S_2	S_3	RHS
S_1	0	0	1	1/3	-1/3	2
X_2	0	1	0	1/2	0	6
X_1	1	0	0	-1/3	1/3	2
Z	0	0	0	3/2	1	36

Table 5, is the optimum table since all the coefficients of objective function (Z) are positive. The optimum value of the objective is 36.

This example was a simple example of simplex method and due to the limited number of constraints and variables, it could be solved by graphical method as follows:

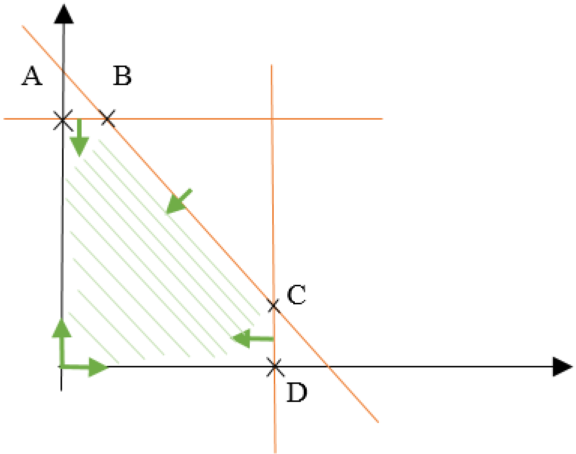


Figure 22: Graphical view of the result of numerical example of simplex method.

B is the optimum point for this example since the objective value for B is better than both A and C which are the two adjacent points of A.

3-2-3-3 Alternative Optimum Solution, Degeneracy, Unboundedness, Infeasibility

A) Alternative Optimum Solution

In the optimum simplex table, if the coefficient of a non-basic variable in the Row Z be equal to zero, it has to select as an entering variable. If the minimum ratio test be not zero, problem has alternative optimum solutions. It means that two or more different points have a same objective value.

B) Degeneracy

In the simplex table, if the minimum ration test would not be unique degeneracy has been occurred. It means that there are more than one variable to enter among basic variables since the value of minimum ratio test are same for them. If the minimum ration test be equal to zero, degeneracy is not solvable. Otherwise, we can leave the degeneracy point.

C) Unboundedness

If one of the non-basic variables has the conditions as an entering variable but there are no minimum ration test to be calculated unboundedness has been occurred. There is no ration test since there is no positive entry in the row of entering variable.

D) Infeasibility

The simplest definition of infeasibility is the set of constraint that have no solution.

There are three possible outcomes for a linear program: it is infeasible, it has an unbounded optimum or it has an optimal solution.

3-2-4 Big M Method

Simplex method starts with a basic feasible solution (BFS) and moves to find an improved BFS, until the optimal point is reached or else unboundedness of the objective function is verified. In order to initialize this algorithm a BFS must be available. In many cases, finding such a BFS is not straightforward and some work may be needed to get the simplex algorithm started. To this end, there are two techniques in linear programming literature: two-phase method and big-M method. But there may be some LP models for which there are not any BFSs, i.e., the model is infeasible. Both two-phase method and big-M method distinguish the infeasibility [44], [45] and [46].

Consider a generic LP model. After manipulating the constraints and introducing the required slack variables, the constraints are put in the format $Ax=b$, $x \geqslant 0$ where A is a m×n matrix and $b \geqslant 0$ is an m×1 vector. Considering **c** as cost vector, the following LP model is dealt with:

$$
\begin{aligned}
& \text{Min } cx \qquad\qquad (P) \\
\text{s.t.} \quad & Ax = b \\
& X > 0
\end{aligned}
$$

Suppose that there is not a starting BFS for simplex method. In this case we shall resort to the artificial variables to get a starting BFS, and then use the simplex method itself and get rid of these artificial variables. The use of artificial variables to obtain a starting BFS was first provided by Dantzig [47].

To illustrate, suppose that the restrictions have been changed by adding an artificial vector Xa leading to the system $Ax + xa = b$, $(x, x_a) \geqslant 0$. This gives an immediate BFS of the new system, namely ($\mathbf{x}=\mathbf{0}$,$\mathbf{x}a=\mathbf{b}$). Even though we now have a starting BFS and the simplex method can be applied, we have in effect changed the problem. In order to get back to the original problem, these artificial variables have to forced to be zero, because

$$Ax=b \Leftrightarrow Ax + x_a = b,\ x_a=0$$

There are various methods that can be used to eliminate the artificial variables. One of these methods is to assign a large penalty coefficient to these variables in the original objective function in such a way as to make their presence in the basis at a positive level very unattractive from the objective function point of view. “P” has been changed to:

$$\begin{aligned} &\text{Min } cx + Mx_a \qquad\qquad (P_M)\\ \text{s.t.}\quad &Ax + x_a = b\\ &x,\ x_a > 0 \end{aligned}$$

Where M is a very large positive number. The term Mx_a can be interpreted as a penalty to be paid by any solution with $x_a \neq 0$. Therefore the simplex method itself will try to get the artificial variables out of the basis, and then continue to find an optimal solution of the original problem. This technique is named the big-M method [46].

CHAPTER FOUR

4-Formulation, Results and Discussion

4-1 Model Formulation

There are several studies about economic analysis of CAES, PV panels and batteries. “Arizona Research Institute for Solar Energy” presented a basic model in their final report named “Study of Compressed Air Energy Storage with Grid and Photovoltaic Energy Generation”. The cost benefit analysis for CAES and PV and the system cost analysis and optimization for the hybrid system had been done in their research. The battery has been added to the hybrid system in the presented model in this study. This model studies the hybrid system in detail and several constraints had been added to the basic model. Most parts of the information about the energy storage systems comes from Sandia report named “DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA”.

The model in this study can find the optimized value in any category including optimized generation for Grid and PV panels and optimized amount of storage for CAES and batteries. Also, this model is able to find the optimized solution with respect to satisfying the demand and reducing the total cost. Analysis of generation and storage performances in the absence of PV panels is another capability of this model. Some days, the irradiance for PV power generation is not enough. Therefore, the system should be able to use another source of energy as a backup power.

In this case, the backup plan can use stored energy in CAES and batteries or increase Grid power generation. Generally, this model needs load demand to provide accurate result for variables. The demand for each day of a year is different, meaning the model has various results for each load profile. But, based on the capacity of the facilities and estimation for using the PV panels, the model can quickly update the optimum amount of generation and storage. In addition to that, sensitivity analysis can be done using this model. The model is able to answer the "what-if….?" questions. For instance, "What if the price of natural gas doubles?" or "What if the final cost of energy produced by PV decrease?".

These parameters will use in this study as follows:

A) Variables:

X_t: The amount of energy in MWh generated during hour t from the Grid to meet the demand

Y_t: The amount of energy in MWh generated during hour t from the PV to meet the demand

Δ **SC_t**: Difference in stored energy level in CAES from period t to t + 1

Δ **SB_t**: Difference in stored energy level in Battery from period t to t + 1

B) Definitions:

SC_t: The amount of potential stored electricity in CAES at the beginning of hour t

SB_t: The amount of potential stored electricity in Batteries at the beginning of hour t

V_t: The value of any stored energy carried over until the hour t

C) Parameters:

t_i : Hours of the day, $t_i \in$ {1, 2,…..,24}

$AC_{(t)}$: Avoided cost of electricity per MWh which is the differences between the cost of energy on peak time and off peak time and it depends on finals price of generated electricity in period t.

$AC'_{(t)}$: show the different price of generated electricity from Grid and PV

RC_{Out}: Maximum CAES's generator rate per hour

RC_{In}: Maximum CAES's Compressor rate per hour

RB: Battery's rate per hour

BC: Battery Capacity at rated depth of discharge

PV_t: PV panels generation in period t

G: Grid capacity

C_F: Fuel cost

f: CAES conversion Factor

e: Battery roundtrip efficiency

D_t: Demand for load during hour t in MW

I: The variable I is an indicator variable equal to one if the subscript condition is satisfied, and zero otherwise.

S: The amount of shortage

S_{max}: Maximum amount of shortage

C_S: Penalty of the shortage

M: Infinite positive number

4-2 Non-Linear Model

The non-linear model is as follows:

Maximize $V_t = I_{\Delta SC(t) \geq 0,\ \Delta SB(t) \geq 0}\,[AC_{(t)}*(\Delta SC_t + \Delta SB_t)] +$

$$I_{\Delta SC(t) \leq 0,\ \Delta SB(t) \leq 0}\,\{-[\Delta SB_t*(AC_{(t)})*e] - [\Delta SC_t(AC_{(t)} - C_F)*f]\} + (AC'_{(t)}*Y_t)$$

S.t.

(1) $SC_{t+1} = SC_t + \Delta SC_t$

(2) $SB_{t+1} = SB_t + \Delta SB_t$

(3) $\Delta SC_t \geq -\min\{SC_t, RC_{Out}\}$

(4) $\Delta SB_t \geq -\min\{SB_t, RB\}$

(5) $\Delta SC_t \leq \min\{Y_t, RC_{In}\}$

(6) $\Delta SB_t \leq \min\{Y_t, RB\}$

(7) $Y_t + \Delta SC_t + \Delta SB_t < PV$

(8) $X_t + Y_t + SC_t + SB_t \geq D_t$

(9) $Y_t \leq D_t$

(10) $Y_t \leq PV_t$

(11) $X_t < G$

$t_i \in \{0, 1, 2, \ldots, 23\}$, $I \in \{0,1\}$, $X_t, Y_t, \Delta SC_t, \Delta SB \geq 0$

4-3 Model Description

In this model, hourly time intervals have been used for ease of study. However, in the real world it can be defined for second to second time intervals. Equation (1) and (2) show levels of stored energy in storage systems at the beginning of next period is equal to levels of the stored energy at the beginning of current period plus the amount of energy which is stored or given from the storage systems in the current period.

When ΔSC_t or ΔSB_t are negative, it means that energy is taken out from the storage system. In inequality (3), energy cannot be taken out from the CAES faster than the maximum generator's rate and more than available stored energy. Similarly, inequality (4) shows that energy cannot be taken out from the batteries faster than the battery's rate and more than available stored energy in the battery.

Inequality (5) and (6) show that energy cannot be charged into the system faster than the maximum compressor's rate and the maximum battery's rate. Also, the difference in energy levels cannot exceed PV generation.

Inequality (7) shows the total amount of stored energy by all storage systems plus part of PV generation that goes for meeting the demand during hour t cannot exceed the PV generation during that time, since PV generation is the only source for feeding all storage systems. Although, most of the time, RC_{In} and RB are smaller than PV generation. PV generation varies day to day and it highly depends on time of a day. It usually has its peak around 10:00 AM to 3:00 PM. In case PV generation is zero, storage systems will be discharged when extra energy is needed and it means ΔSC_t and ΔSB_t are negative and inequality (7) still will be satisfied.

Inequality (8) can guarantee that we do not have any shortage in the system, because in each period, generation plus stored amount of energy should be equal to or greater than demand. Shortage can be added to this model, but maximum amount of shortage and the penalty for the shortage should be considered.

(8') $X_t + Y_t + SC_t + SB_t - S \geq D_t$

(12) $S \leq S_{max}$

Inequality (9) and (10) show that the part PV generation that goes for meeting the demand cannot exceed the demand and PV generation. Inequality (11) is the capacity limitation for the grid generation.

In the objective function, it has been assumed that storage systems don't have energy at the beginning of the day (t=1). The value of energy at this period is equal to difference between avoided cost and the cost for taking out the stored energy multiplied by CAES convention factor (f) or battery efficiency (e).

To take out energy from CAES fuel cost (C_F) need to be paid. CAES uses fuel to preheat the air before putting air into the generator to increase the efficiency of the storage system. Objective function calculates the value of energy for periods of a day. It depends on the stored energy taken out or given into each energy storage system.

There are two possible states for ΔSC_t, ΔSB_t. They are either both greater than or equal to zero or less than or equal to zero. It means that there is no situation when $\Delta SC_t \geq 0$ and $\Delta SB_t \leq 0$ or vice versa. The reason is when there is not enough generation to meet the demand, PV generation would be used to compensate the shortage and if it wasn't enough either of the two storage systems will be used so, there is no more PV generation to feed the other one.

Objective function is highly depended on the avoided cost (AC_t) and (AC'_t). AC_t has been added to system to show the effect of different price of electricity generation during a day. AC'_t is added to the system to show the different price of generated electricity from Grid and PV. AC_t always vary from a period to another period. It is obvious that the load profile of demand has a great impact on the prices. Consequently, by fluctuating in demand, electricity prices fluctuate constantly. For instance, price of electricity in 10:00 AM is cheaper than 10:00 PM. Therefore, avoided cost (AC_t) has been selected to show the impact of different price of electricity during a day. As an example, if the storage systems start charging on off peak demand periods when the prices are lower, avoided cost (AC_t) has greater value compared to situation when storage systems start charging on high peak demand periods since, price of electricity is different in off peak and high peak periods. Therefore, electricity prices can change the optimum solution for generation and storage planning since higher electricity prices lead to lower avoided cost.

Fuel cost (C_F) is one of the most important parameters in this model due to its fluctuation. Energy will be stored in CAES as long as fuel cost has reasonable value compared to the avoided cost for using CAES.

Load profile is fluctuating inherently and it changes second to second. It depends on different occasions in each day. Therefore, the exact amount of demand is always unknown and we only have an estimation based on the previous data.

Variable I is 1 when the subscript condition is satisfied and zero otherwise.

4-4 Model Assumptions

The presented model is general and can be used in any system consists of grid and PV generation, CAES and batteries. In this section, some assumptions will be used for ease of study.

- Hourly time intervals have been used
- The level of stored energy at the beginning of each day (t=1) have been assumed to be zero.
- PV is the only source feeding ESSs.
- All hybrid system’s components are already existed and there is no capital investment.
- No storage system can be charged while, the other ESSs are discharging.
- Shortage is not allowed in this model.
- It has been assumed that one type of battery is being used in this system.

- Demand is constant during each time interval.
- Grid generation is always constant during a day for all intervals.
- Due to the final price of electricity, first priority for meeting the demand is by PV and then Storage systems. Grid is the last option for responding to unmet demand.
- It has been assumed that there is not priority between CAES and battery.
- It has been assumed that energy loss is zero.

4-5 Model Analysis

4-5-1 Cost

As mentioned earlier, this model can have different objectives. For instance, one of the common objectives is based on the cost and define the best set of variables to minimize the cost. This model supposes that all the facilities are existed and there is no extra cost for buying a new ESS.

Capital investment is one of the most important parameters for investors. To modify this model, we can assume the network already has CAES and PV panels but, batteries are an optional choice to reduce the cost, shortage and etc.

Batteries can be used for short term storage to shave the peak periods in load profile. Sometimes, load is not that much high to expand air into CAES. In this case, batteries can give energy to the system to reduce total cost, increase CAES and network efficiency, and reduce fuel consumptions. All these decisions need accurate analysis. In this scenario, capital investment for the batteries can be added to the objective. Also, by using this model, comparison between different batteries can be done.

Each battery has several attributes like capacity, depth of discharge, capital investment, power rate and etc. One step further, we can find the optimum number of each type of batteries. Different objectives can be defined based on the cost because, there are different kinds of cost associated with ESSs. Moreover, we can specify the objective function to maximize the value of energy carried over each period.

This model is able to do sensitivity analysis for variables by investigating effects of natural gas price fluctuation on the total cost. CAES is one of the ESSs that uses natural gas to preheat the compressed air to increase the efficiency of the storage system. So, to use stored energy a fuel cost (CF) need to be paid. On the other hand, when energy is stored in CAES, the amount of AC_t will be saved. That is why fuel cost is considered in objective function.

Sensitivity analysis is able to answer what-if questions like what will happen if the price of natural gas or fuel gas increases 2 percent. Therefore, the impact of fuel cost fluctuation on the system can be find because, change in one variable leads to different values for other variables.

4-5-2 Energy Storage System Attributes

There are different kinds of batteries, PV panels and CAES. This model can analyze and compare different kinds of each storage system. For instance, an analysis can be done between 1000KW and 2000KW of Lithium-Ion battery. This model can find what will happen if the CAES capacity increase for example from 322MW to 441MW. Each of these scenarios have different associated costs and model will find the best solution with various input data and objective function.

Size of storage devices is an important parameter for many applications. For a given amount of energy, the higher the power and energy densities are, the smaller the volume of the required energy storage system will be. Lifetime and cycling times are two factors which affect the overall investment cost. Low lifetime and low cycling times will increase the cost of maintenance and replacement.

4-6 Optimization and Simulation

Optimization is a method to find the optimum or near to the optimum solution for a model with respect to the objective and constraints. Optimization methods try to find the best value for variables to satisfy the constraints and maximize or minimize a real objective from a set of alternative solutions. To solve operational research problems there are different methods like Genetic Algorithm, Dynamic Programing, Integer Programing, Linear Programing, Non-linear Programing and etc. [48].

The presented model in this study is a kind of Non-Linear Programming. Based on the operation Research principles, the non-linear model has been transformed to a linear model to be solvable with any operation research method or software.

As mentioned earlier, load demand is not a constant value and it fluctuates second to second. Moreover, some other inputs like PV generation and natural gas price are fluctuating constantly. Moreover, each interval of a day is somehow depended on the other periods. The amount of energy carried over each period impacts on the amount of generation and storage of current period. To find the accurate optimum value for the objective, model should be updated every time that one of the inputs changes.

On the other hand, simulation techniques usually use for more complex models when the input variables change a lot. Simulation methods try to find the behavior of a real model over the time. Simulation is able to answer what if questions about changes in the model. When one or more inputs change over the time, simulation software can update the model quickly and do the analyses under the new conditions. Although, there is no guarantee in simulation methods to find the optimal solutions but, they are still the best way for the systems which change constantly.

The optimization is useful for the strong models with known inputs while simulation is being used in the situations which inputs are conditional and dynamic. Since some inputs of this model change a lot, simulation can be run to find a solution for a set of variables. Although, by defining a constant value for inputs, optimization can s find the solution.

4-7 Linear Model

The non-linear model has been transformed to a linear model as follow:

Maximize $V_t = I * [AC_{(t)}*(\Delta SC_t + \Delta SB_t)] +$

$$(1\text{-}I)\ \{-[\Delta SB_t\,(AC_{(t)}) * e] - [\Delta SC_t\,(AC_{(t)} - C_F) * f]\} + (AC'_{(t)} * Y_t)$$

S.t.

(1) $SC_{t+1} = SC_t + \Delta\, SC_t$

(2) $SB_{t+1} = SB_t + \Delta\, SB_t$

(3) $(-)\ \Delta\, SC_t \leq SC_t$

(4) $(-)\ \Delta\, SC_t \leq RC_{Out}$

(5) $(-)\ \Delta\, SB_t \leq SB_t$

(6) $(-)\ \Delta\, SB_t \leq RB$

(7) $\Delta\, SC_t \leq Y_t$

(8) $\Delta\, SC_t \leq RC_{In}$

(9) $\Delta\, SB_t \leq Y_t$

(10) $\Delta\, SB_t \leq RB$

(11) $Y_t + \Delta\, SC_t + \Delta\, SB_t < PV$

(12) $\Delta SC_t > (1\text{-}I)*(-M)$

(13) $\Delta SB_t > (1-I)*(-M)$

(14) $\Delta SC_t < IM$

(15) $\Delta SB_t < IM$

(16) $X_t + Y_t + SC_t + SB_t \geq D_t$

(17) $Y_t < D_t$

(18) $Y_t \leq PV_t$

(19) $X_t < G$

$t_i \in \{0, 1, \ldots, 23\}$, $I \in \{0,1\}$, $\{X_t, Y_t, \Delta SC_t, \Delta SB\} \geq 0$

Each of the inequalities of (3), (4), (5) and (6) have been transformed to two separate inequalities to eliminate Min function. In non-linear model, objective function was not linear. Equations (12), (13), (14), and (15) are the linear substitution for objective function to define the amount of "I" and satisfaction of the subscripts. The value of "M" that has been added to linear model is an infinite positive number.

4-8 Numerical Example

In this section, an example is presented to illustrate the numerical calculation of some parameters like avoided cost (AC) for one period and fuel cost (CF). To apply Operation Research methods or simulation software, the value of these attributes must be known. Although, these values vary in each time interval.

CAES attributes are as follows: [4]

- CAES Capacity: 13 Hours at max generation
- RC_{In} is 600 MW per hour

- RC_{Out} is 500 MW per hour
- 0.75 KWh of power used to store energy yields 1.0 kWh of energy while combined with 4300 BTU of natural gas. f = 1/0.75=1.33

As an example, Lead-Acid battery has been selected: [3]

- BC is 10,000 KW
- Hours of energy storage at rated capacity is 2
- Depth of Discharge is 85% per cycle
- RB is 1C rated, 10,000 KW per hour
- e is 90 %
- 20 Battery exist in the system

The value for other parameters in this assumption are as follow:

- C_F is \$0.080 per KWh [48]
- PV capacity is 10000 MW [4]
- AC is different for each period of a day. As an example, \$0.277 (per KWh on peak) - \$0.058 (per KWh off peak) = \$0.219 [13]. It is not always a constant value even in a day and it depends on the electricity generation prices.
- PV and Grid generation and demand profile depend on the time of a day.

As mentioned earlier, this model can have different functions. In this example, shortage is not allowed in this network. Consequently, this model tries to find the results to meet the whole demand. Cost function can be used as a target to minimize the cost based on the associated cost like generation cost, avoided cost, natural gas cost and etc. For real problems, different cost parameters can be added to the model.

In this example, we used a Lead-Acid battery while in real cases, different types and numbers of batteries can be tested and be compared. Although one of the assumptions is that one type of batteries being used in this system, it's possible that the optimal solution offers a mix of various kinds of batteries if different types of batteries add to the system. Unlike the batteries, types of CAES are limited but, still a comparison between underground or above ground CAES with different system size can be done by using this model. In this example, it is assumed that the network has all the storage systems but, most of the time, the capital cost of ESSs is expensive enough to change the results. Therefore, in real cases, the capital cost, maintenance cost and other types of cost associated with ESSs should be considered.

Some of the parameters are estimated and it's not possible to find the exact value for them. In presence of uncertainty, sensitivity analysis can be done to illustrate the effect of changing a parameter on the final solution. For instance, natural gas price is fluctuating constantly and it is not accurate enough to use a constant value. On the other hand, estimating the CF (Fuel Cost) based on dollar per KWh depends on several factors like the CAES system's attribute. Sensitivity analysis can find what will be the result if one of the parameters like CF change. Sensitivity analysis is able to provide a range for each parameters to keep the same optimal solution.

Based on this model, hybrid system can consist of one of the following scenarios:

- Grid without ESSs
- Grid + CAES
- Grid + Batteries
- Grid + CAES + Batteries
- Grid + PV without ESSs
- Grid + PV + CAES

- Grid + PV + CAES + Batteries

As mentioned earlier, the demand and PV panels generation are not constant values. To complete this example, demand and PV generation have been assumed for 24 periods of a day as follows:

Table 6: Assumptions of numerical example

t_i	D_i	PV_i	AC_t	t_i	D_i	PV_i	AC_t
0:00	900	0	0.15	12:00	7000	8000	0.20
1:00	800	0	0.12	13:00	7500	8000	0.19
2:00	800	0	0.08	14:00	7500	7500	0.15
3:00	1000	0	0.05	15:00	7200	7000	0.15
4:00	1600	0	0.02	16:00	6400	6000	0.18
5:00	2400	0	0.02	17:00	5300	4000	0.20
6:00	3200	4000	0.05	18:00	7000	4000	0.21
7:00	3200	4000	0.10	19:00	7500	3000	0.22
8:00	4000	4500	0.10	20:00	8000	2000	0.22
9:00	4600	5000	0.15	21:00	7500	1000	0.22
10:00	5600	6000	0.16	22:00	7000	0	0.22
11:00	6400	7000	0.16	23:00	6000	0	0.22

The variables are X_t , Y_t , Δ SCt and Δ SB_t. Each period of a day is dependent on the other periods especially last period. Therefore, to solve this example we have to start from first period. As mentioned earlier, it has been assumed that levels of stored energy in storage systems at the beginning of a day are equal to zero. The objective function of this example is maximizing the value of energy carried over period t_i.

The assumed values for this model has been substitute for t=0 as follows:

$$\text{Maximize}\ \ V_t = I * [AC_{(t)} * (\Delta SC_t + \Delta SB_t)] +$$

$$(1\text{-}I)\ \{-[\Delta SB_t\,(AC_{(t)}) * 0.9] - [\Delta SC_t\,(AC_{(t)} - C_F) * 1.33]\} + (AC'_{(t)} * Y_t)$$

S.t.

(1) $SC_{t+1} = SC_t + \Delta\ SC_t$

(2) $SB_{t+1} = SB_t + \Delta\ SB_t$

(3) $(-)\ \Delta\ SC_t \leq SC_t$

(4) $(-)\ \Delta\ SC_t \leq 500$

(5) $(-)\ \Delta\ SB_t \leq SB_t$

(6) $(-)\ \Delta\ SB_t \leq 200$

(7) $\Delta\ SC_t \leq Y_t$

(8) $\Delta\ SC_t \leq 600$

(9) $\Delta\ SB_t \leq Y_t$

(10) $\Delta\ SB_t \leq 200$

(11) $Y_t + \Delta\ SC_t + \Delta\ SB_t < PV$

(12) $\Delta SC_t > (1\text{-}I)*(\text{-}M)$

(13) $\Delta SB_t > (1\text{-}I)*(\text{-}M)$

(14) $\Delta SC_t < IM$

(15) $\Delta SB_t < IM$

(16) $X_t + Y_t + SC_t + SB_t \geq D_t$

(17) $Y_t < D_t$

(18) $Y_t \leq PV_t$

(18) $X_t < 20000$

$t_i \in \{0, 1, 2, \ldots\ldots, 23\}$, $I \in \{0,1\}$, $\{X_t, Y_t, \Delta SC_t, \Delta SB_t\} \geq 0$

Price of electricity which comes from Grid is higher than price of generated electricity from PV panels. In this model, it has been assumed that PV is the only source for feeding the storage systems. It means that it doesn't have economic justification to store the electricity that comes from Grid. Although, in real world it may happen to prevent shortage but it this model it has been assumed that PV is the only source for feeding storage systems.

To start solving this model, it has been assumed that level of stored energy in storage systems is equal to zero at starting of the first period. For next days, energy can be carried over from a day to next day. In t=0, PV doesn't generate electricity and grid is the only source for meeting the demand till PV starts generation in the morning. "Figure 22" shows the graphical result of this example. It represents the demand profile, Grid generation, PV generation and level of stored energy in storage systems.

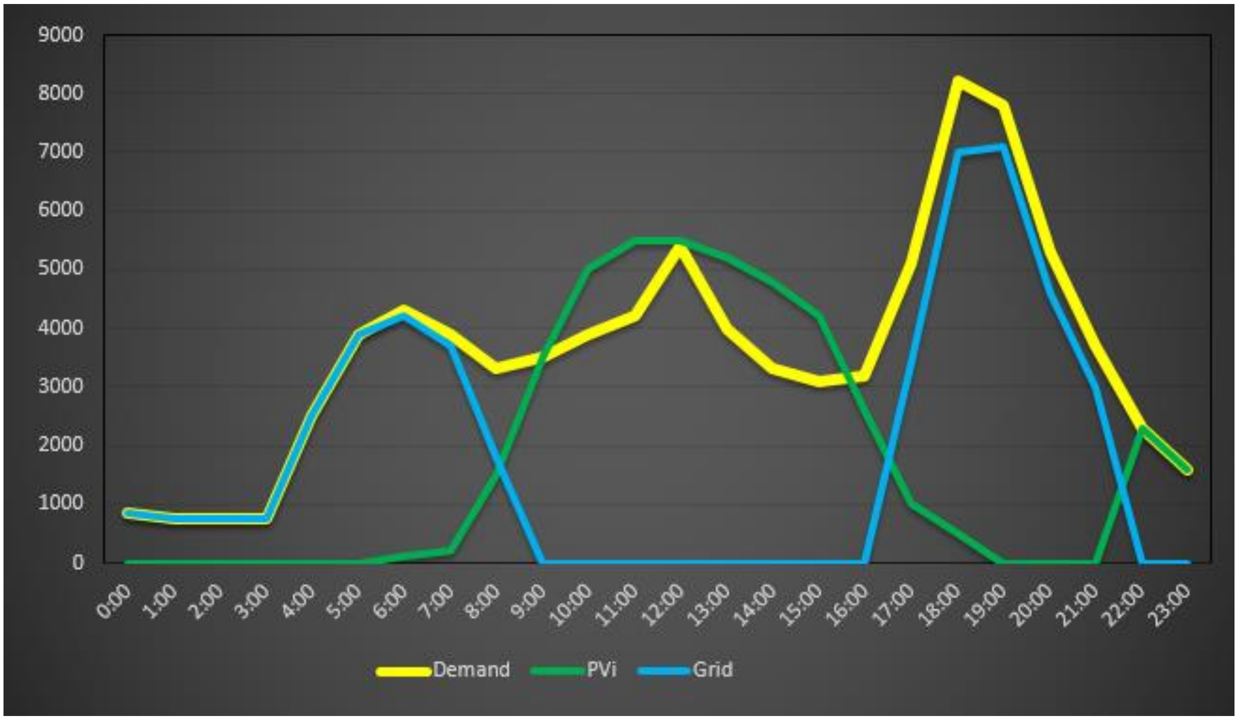


Figure 23: Load Profile, PV Generation and Grid Generations for the numerical example.

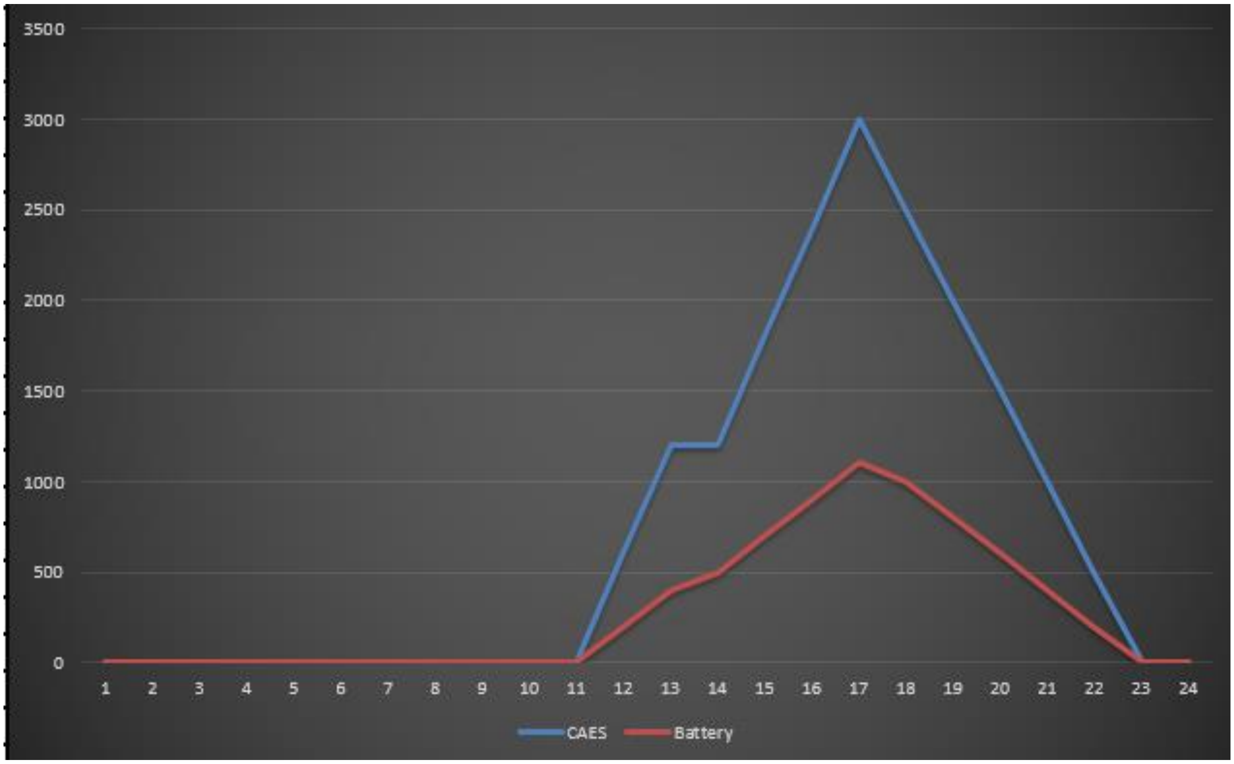


Figure 24: State of charge of CAES and battery for the numerical example.

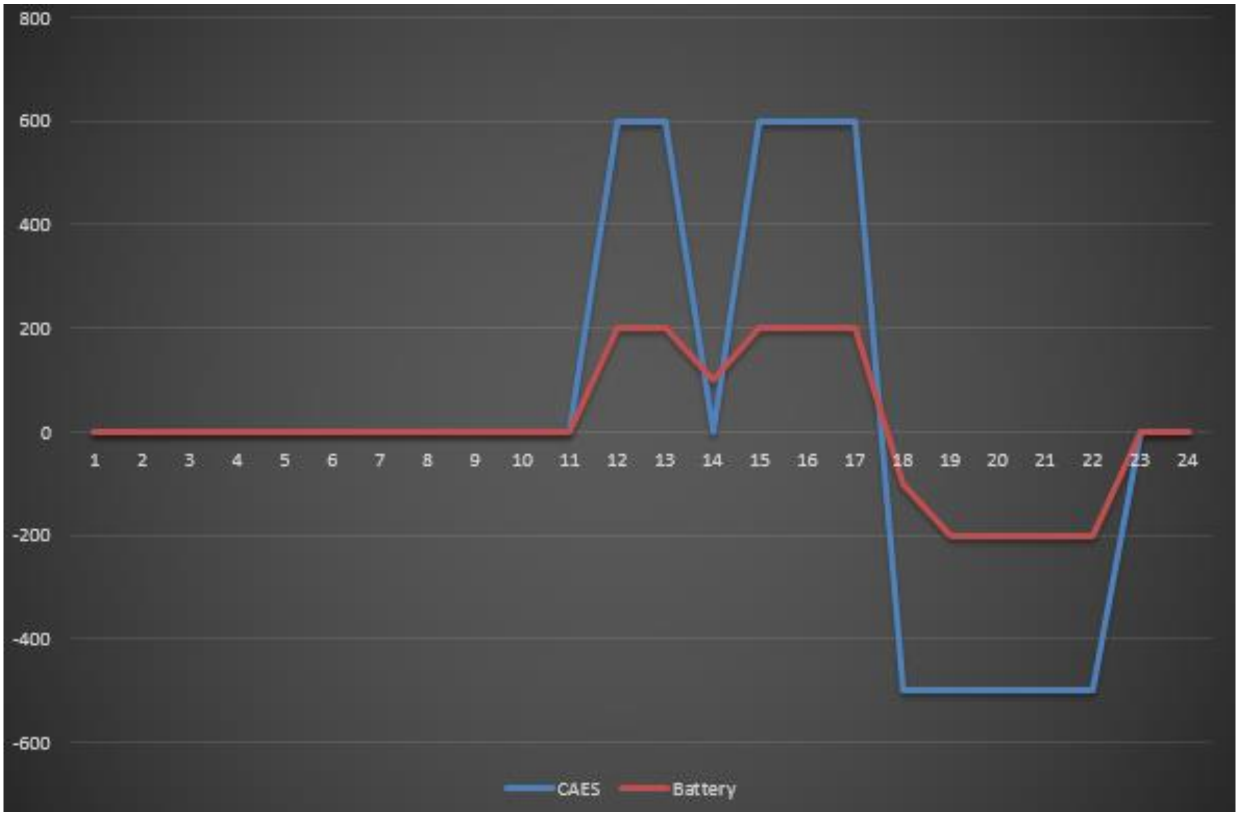


Figure 25: Power profile of the CAES and battery for the numerical example.

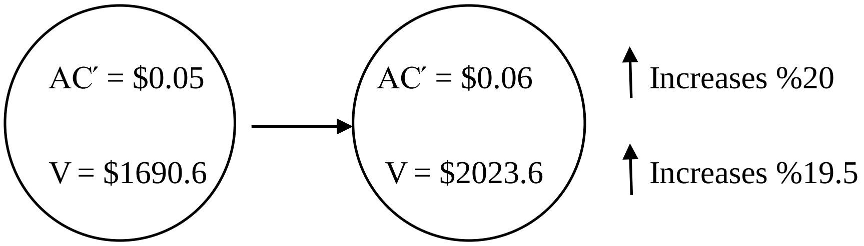
Table 7: Final results of the numerical example.

t_i	X_t	Y_t	ΔSC_t	SC_t	ΔSB_t	SB_t	V_t
0:00	850	0	0	0	0	0	0
1:00	750	0	0	0	0	0	0
2:00	750	0	0	0	0	0	0
3:00	750	0	0	0	0	0	0
4:00	2500	0	0	0	0	0	0
5:00	3900	0	0	0	0	0	0
6:00	4200	100	0	0	0	0	5
7:00	3700	200	0	0	0	0	10
8:00	1800	1500	0	0	0	0	75
9:00	0	3500	0	0	0	0	175
10:00	0	3900	600	0	200	0	199.8
11:00	0	4200	600	600	200	200	215.6
12:00	0	5400	0	1200	100	400	270.8
13:00	0	4000	600	1200	200	500	205.6
14:00	0	3300	600	1800	200	700	171.4
15:00	0	3100	600	2400	200	900	162.2
16:00	0	2600	-500	3000	-100	1100	125.2
17:00	3400	1000	-500	2500	-200	1000	50
18:00	7000	500	-500	2000	-200	800	25
19:00	7100	0	-500	1500	-200	600	0
20:00	4600	0	-500	1000	-200	400	0
21:00	3000	0	-500	500	-200	200	0
22:00	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0

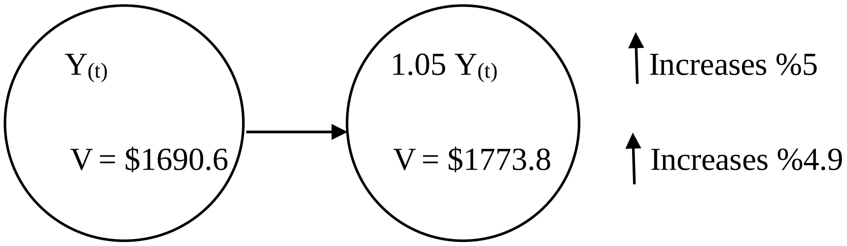
For this example, V_t is equal to $1690.6. It shows the value of energy, which has been stored by energy storage systems and the value of energy that generated by PV panels for a day in this example.

By using this model, sensitivity analysis can be done for parameters. For instance, If AC′ increases %20, V will be increased %19.5. It means that V is highly depends on AC′. As an another example, if $Y_{(t)}$ increases %5, V will be increased %4.9. Therefore, V is too sensitive to $Y_{(t)}$ and AC′.

1)



2)



CHPATER FIVE

5- Conclusion and Scope of Future Research

Energy resource management is one of the most attractive topics in the last decades. Scientist from all around the world try to use energy resources more efficiently. Traditional resources are going to deplete if they are used as a primary source of energy. Renewable energy resources have been emerged to help traditional resources, increase efficiency, decrease pollution, help the environment, etc.

Renewable sources are clearer than traditional sources and are renewable quickly. One of the problem associated with renewable sources is availability. They are not always available like traditional resources. As an example, wind is not always the same speed, and climate changes have a great impact on the output of wind turbines. Another example of renewable sources is solar PV panels, which highly depend on the irradiance and climate. Because renewable energy sources are not always available the reliability of the hybrid system will be decreased. Traditional sources were more reliable than renewable sources. Adding energy storage systems can help the hybrid system to increase the reliability of the system.

Energy storage systems can charge whenever that the energy source is available or the price of electricity is less than peak demand. Storage systems can discharge during peak demand periods. Also, they can be used as a backup for energy source or when the energy should be transported to another location.

In this research, several types of energy storage systems have been studied in detail. The topic is mainly focused on a hybrid system consisting of grid generation, renewable energy sources and energy storage systems. The main purpose of this research was modeling and formulating a hybrid system with respect to the most important constraints. This model can be studied in more detail from various aspects by using different tools and methods of operation research. Generally, when the model is ready, most of the analysis can be done more easily.

In this study, the hybrid system consist of Grid generation, PV generation, Compressed Air Energy Storage and battery. The grid can feed the system in cases which the PV generation and storage systems cannot respond to the demand. PV generation depends on the time of the day and weather conditions. Battery is the common storage system which has been widely used to store energy when the shortage is not too high or the storing period is not too long. Compressed air energy storage can store the energy for longer periods of time and in larger amount. Recently, researchers added fuel to preheat the gas before expansion to increase the efficiency of the system. As a result, CAES uses natural gas to store and release the electricity.

For ease of study, some assumptions have been made. The presented model was first nonlinear, since there were non-linear relation between some parameters. Using the big M method could transfer the model to a linear one. The linear model can be solved by Simplex method, Operation Research software like Math-lab or Simulation software like Simulink. All the parameters should be specified to get a result.

The demand for electricity is not a constant value and it varies minute to minute. Based on the demand, this model can find the best set of solutions for variables to maximize the value of energy carried over and determine a schedule for charging and discharging the storage systems for each day. The presented model is a theoretical model and in the real world, some assumptions may be different.

Operation Research softwares need a linear model to find the optimum solution. So in this study a linear model has been presented to make the mathematical model ready for software or manual calculation. Using this model, sensitivity analysis can be done for some of the parameters such as fuel cost to see the impact of any change on the objective value.

For further studies, PV panels can be studied more accurately with respect to irradiance and reliability. Different types of batteries or a mix of other energy storage systems can be added to the hybrid system. To have a more reliable system, wind turbines can be added to the system to smooth out the generation, since PV and wind sources are complementary during a day.

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