ISLAMIC UNIVERSITY OF TECHNOLOGY

OPTIMAL SIZING OF PV/WT/CSP/TES/HFC-BASED HYBRID RENEWABLE ENERGY SYSTEMS

Mueed Shadman (180021310)

Mohammad Fahim Hossain (180021309)

Ahmed Istiakur Rahman (180021304)

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DECLARATION

We, the authors of this report entitled "OPTIMAL SIZING OF PV/WT/CSP/TES/HFC BASED HYBRID RENEWABLE ENERGY SYSTEMS", hereby declare that this report and all the findings presented in it are our own.

Submitted by:

Mueed Shadman
Student ID:
180021310

Mohammad Fahim
Hossain

Student ID:180021309

Ahmed Istiakur
Rahman

Student ID:180021304

Certificate of Approval

The submitted report of our project entitled, “OPTIMAL SIZING OF PV/WT/CSP/TES/HFC BASED HYBRID RENEWABLE ENERGY SYSTEMS” submitted by Mueed Shadman, St. No. 180021310, Mohammad Fahim Hossain, St. No. 180021309, Ahmed Istiakur Rahman, St. No.180021304 of Academic Year 2018-19 has been approved on 19 May 2023.

Approved by:

Dr. Ashik Ahmed (Supervisor)
Professor,
Department of Electrical and Electronic Engineering
Islamic University of Technology (IUT), Gazipur.

Acknowledgment

"All praise and gratitude be to Allah, the most beneficent, the most merciful."

We can never deny the endless mercy bestowed upon us by the Almighty Allah (SWT). At the very beginning, therefore, we express our deepest gratitude to the Almighty for granting us the wisdom and capability to reach this far with the successful completion of this work.
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Abstract

In recent times continuous increases in fuel prices and greenhouse gas emissions have demanded the transition to a 100% renewable energy system. However, with the increase of renewable sources requirement for battery storage systems also increases. Battery storage is making hybrid systems expensive and increasing their carbon footprint. One another hindrance to using solar power is their low reliability in large-scale use. This study aims to explore and analyze the optimal sizing techniques for a system consisting of photovoltaic (PV), wind turbines (WT), concentrated solar power (CSP), thermal energy storage (TES), and hydrogen fuel cells (HFC) in order to achieve efficient, reliable, and cost-effective designs of hybrid renewable energy systems. The primary objective of optimal sizing is to balance the energy supply and demand while considering the availability and intermittency of renewable energy resources. This involves a thorough analysis of the potential energy generation from PV, WT, and CSP systems. In this study, loss of power supply probability (LPSP) is used for ensuring power supply and a new index DLP is proposed to minimize the dump load requirement. To achieve optimal sizing, modeling and simulation techniques are employed in the MATLAB platform. This study uses one of the most popular metaheuristic optimization technique PSO (particle swarm optimization) and compares the result with two recently proposed optimization algorithm, Pelican optimization algorithm and the Dandelion optimization algorithm. The study shows Dandelion optimization algorithm gives the best result for PV/WT/CSP/TES/HFC configuration. In conclusion the integration of PV, WT, CSP, TES, and HFC technologies in hybrid systems presents a promising pathway toward achieving a cleaner, efficient and more sustainable energy future.

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CHAPTER 1

INTRODUCTION

1.1 Background:

Mother Earth is currently experiencing a major global challenge: the energy crisis. This problem is the result of multiple linked challenges, including rising energy consumption, fossil fuel reserve depletion, rising energy costs, and the negative effect of traditional energy sources on the environment. As the world's population and economy continue to develop, the requirement for sustainable and secured energy sources has grown critical.

The backbone of energy production has been energy sources like coal, natural gas, and other fossil fuels, etc. The usage of fuels has had exponential growth since the industrial revolution and this growth has made a catastrophic impact on the environment. The impact has two main sides, the burning of fossil fuel and the mining and combustion of the same. Fossil burning has led to an increase in carbon dioxide which is impacting global warming and climate change. Mining and combustion have led to environmental degradation.

As the whole world is facing the brunt of the energy crisis, the most viable path that seems feasible is renewable energy sources. Renewable energy are energy sources that are restocked by the environment naturally such as sunlight, wind, water, and biomass. Photo voltaic (PV)panels are efficient, cost-effective, and widely available. Wind turbines use the kinetic energy of wind to generate electricity. Concentrated solar power (CSP) concentrates solar radiation, producing thermal and electrical power. Thermal energy storage (TES) adds a new domain to renewable sources making the whole project more environment friendly. Hydrogen fuel cells (HFC) utilize excess energy from the hybrid plant ensuring more efficient usage of utilities. As the world is facing an energy crisis, we aim to utilize certain renewable energy components PV/WT/CSP/TES/HFC and integrate them to form a sustainable, environment-friendly and cost-effective system that will help mitigate crisis to a certain extent.

1.2 Motivation:

The main motivation behind pursuing this project stems from the current energy crisis. The energy crisis has hit the world hard and pushed us to brakes. Human economic activity is severely disrupted and limited by this. In Bangladesh, load shedding has increased by many folds which has impacted the lives of all sections of people. Power plants are getting burdened with increasing demand but replenishing resources. With all the aforesaid reasons in mind, we decided to embark on the journey of helping our country integrate renewable energy sources and reduce the impacts of the energy crisis.

Because of the intermittent nature of renewable energy sources, optimal scale is crucial. By appropriately measuring the capacity of each component, including energy storage devices, the hybrid system may efficiently store additional energy during peak generating times and utilize it during low generation periods. This improves the reliability and stability of the energy supply, ensuring a consistent and uninterrupted power source. The entire system cost may be reduced by identifying the proper mix of component capacities, making renewable energy solutions more appealing and financially possible for adoption.

Finally, the necessity to address the energy crisis, decrease environmental effects, improve energy dependability, and promote sustainable economic growth drives the optimal scaling of hybrid renewable energy systems based on PV/WT/CSP/TES/HFC. We can harness the full potential of renewable energy sources by attaining optimal scaling, paving the path for a greener and more sustainable future.

1.3 Objective

The main objectives of our study that we target to achieve are:

- Design a low-cost hybrid system containing PV/WT/CSP/TES/FUEL CELL.
- Design a reliable and efficient system.
- Design a system that has 100% renewable share.
- Compare the feasibility of three optimization algorithm for our design

CHAPTER 2

Literature Review

2.1 Hybridization of the Sources

Renewable energy sources are variable and uncertain in nature. Thus, energy security is a big concern. Researchers suggest two ways to tackle the variable and uncertain nature of renewable sources. One is to add a storage system and another option is to add multiple renewable sources.

Each region of the world has its unique climate characteristics depending on location, altitude, topology, distance from the equator, average humidity, temperature, air pressure, etc. That's why the choice of renewable sources to make a hybrid system is a matter of research. Again, there is a question of the economics of sources. Sometimes it is more beneficial to go for hybridization between diesel generators and renewable sources than go for zero fuel structure. So, the choice of renewable energy source type is a big challenge.

This part of the literature review will discuss what the recent projects are choosing as renewable sources and different mixing/hybridization options.

Abolfazl Ghaffari et al. proposed an efficient and reliable hybrid system using PV, a Fuel cell system containing an electrolyzer, hydrogen tank, and diesel generator. Excess energy generated from the PV panel was stored in the hydrogen tank in the form of hydrogen and a diesel generator was used as a backup power generation option when renewable sources failed to meet the load demand [1].

Asif Khan et al. adopted a zero-fuel system and replace diesel generators with wind turbines and built a PV-WT-FC system. In their study, they found that for 98% of the energy availability index, the PV-FC combination is more economical than   PV-WT-FC or WT-FC combination [2].

The authors in [3] proposed these same 3 options mentioned in [2] with battery storage systems in four regions of Iran. This study revealed the most significant reasons why FC are still lacking popularity albeit having tremendous potential benefits. Ramim Hosseinalizadeh et al. found that for non-hybrid systems, PV with storage is more economical than WT with storage. Moreover, for a hybrid system, it is wise to exclude FC from the system and go for the PV-WT-BATTERY combination because of the high initial cost and low replacement life of the fuel cell. Anand Singh et al. investigated the reliability of fuel cells and battery storage to power an academic research building in India during late night and early morning hours [4].

The author introduced two new components in [5] for more dynamic, efficient, and dependable operation. The PV-WT-FC system was connected to the grid for greater reliability. A CHP unit, or combined heat and power unit, was used to utilize the heat generated by the fuel cell and the rest of the system to meet the household's heat energy needs

In recent years, researchers have been developing systems for fully dispatchable power supply utilising only solar energy. Large-scale PV and wind systems produce erratic frequency and voltage. Furthermore, PV and wind turbine regulation and control are tough. Concentrated solar power (CSP) can be used for long-term use and large-scale electricity production. As opposed to a high-cost battery storage system, it provides a more dispatchable power source with a low-cost thermal storage system (TES). Hongtao Liu et al. conducted a literature study and discovered that combining PV and CSP reduces LCOE by 1.5-7% and reduces solar field size by 30-40%. The capacity factor for the combination of CSP-PV was improved by up to 90%.[6]

Author in [7] studied the same configuration as [6] and showed that for a daily operation of more than 16 hours, CSP is the best option, and for a daily operation of fewer than 8 hours, PV system was found to be more economical. However, if the daily operation time lied in between 8 to 16 hours then a hybrid system of PV-CSP is the more cost-effective solution.

Sara Ghaem Sigarchian et al. studied the optimum design of a PV-CSP-LPG generator with battery storage and thermal storage. Their study concentrated on a more reliable, more flexible, and less environmental footprint solution.[8]

Mohamed Ali Abaza et al. designed a 10 MW CSP plant operated 100% by solar energy. It optimized the thermal storage size for a 100% solar-powered system and found the perfect thermal cycle among the open gas cycle, steam Rankine cycle, and organic Rankine cycle.[9]

E. Casati et al. focused on the optimal operation of thermal storage for CSP plants. They studied the effect of different types of thermal storage material effective for two locations, i.e., Daggett (US-CA) and Almeria (ES). [10]

The author of [11] compared 4 configurations; config-1 (Biogas-Biomass-PV-WT-FC-Battery), config-2(PV-WT-Biogas-Biomass-FC, without battery), config-3(PV-WT-Biogas-Biomass-battery, without FC) and config-4(PV-WT-Biogas-Biomass, without storage). Among these combinations, config-1 is the most economical one. Biogas and Biomass are very popular in rural regions.

Weiping Zhang et al. used artificial neural networks to accurately estimate solar radiation, ambient temperature, and wind speed in a stand-alone solar wind-hydrogen energy system [12].

Monotosh Das et al. investigated a less popular storage solution and found it to be effective. They investigated the PV Biogas generator-pump hydro energy storage-battery system and compared the performance of several metaheuristic algorithms on this arrangement.[13]

Barun K. Das et al. studied PV-WT-Biogas-based HRES for a remote island called “Saint Martin” in Bangladesh and applied a multi-objective optimization technique (cost of energy and life cycle emission).[14]

In [15], the authors analysed wind/battery, PV/battery, and wind/PV/battery systems with constant DC link voltage and constant AC output voltage, regardless of load demand, wind speed, or solar irradiance fluctuations.

A.Khan Faizan et al. considered PV/ wind for making 7 combinations and tried to optimize them for economic, environmental, and social indicators. Among the 7 combinations, the photovoltaic/wind/diesel/generator/battery combination proved to be satisfying all the constraints at the lowest cost.[16]

2.2 Reliability Indices:

The hybrid system must provide low-cost energy with security. Otherwise, it will be difficult to motivate the common people and government policymakers to shift from conventional fuel-based power plans to hybrid renewable energy plants.

In this part of the literature review, we will review different types of reliability indices used throughout these years to ensure the energy security of the HRES designs.

Loss of power supply probability (LPSP) is the most popular reliability indices used in the literature [1-19]. LPSP is defined as the percentage of power supply that is not able to satisfy the load demand. It is calculated in two ways, one as the ratio of unmeet power to total produced power and the second one as the ratio between the total time when the system fails to supply power to the total time of the study [20].

Mohamed Atef et al. used the Loss of Load Probability Index (LOLP) to optimize a hybrid PV and Gas turbine generator system [21]. LOLP is defined as the ratio of total energy shortage (kWh) during a time (t) to total load demand (kwh) in that time(t).

Sarangthem Sanajaoba and Eugene Fernandez used Loss of load expected (LOLE) and Expected energy not supplied (EENS) as reliability indices. LOLE is the average number of hours when the load exceeds the system capacity and EENS is the total energy expressed in kWh that the available generation capacity will not be able to supply. [22]

The author in [23] tried to optimize an off-grid PV-WT system using Deficiency of power supply probability (DPSP). DPSP represents the possibility of an insufficient power supply situation when the system cannot meet the load demand.[23]

E.L.V. Eriksson et al. in their literature review mentioned another reliability indiceswhich is Loss of load risk (LOLR). LOLR refers to the risk of an electric power system being unable to meet the demand for electricity, resulting in a blackout or loss of power supply.[24]

In addition to the above commonly used reliability indices, there are some more indices used by many researchers, such as unmeet load (UL) [25], probable loss of power probability (PLPP) [26], level of autonomy (LA) [27], etc.

2.3 Economic Index

The main purpose of mixing different types of renewable sources is to reduce uncertainty and cost of energy. The economic index is very important to assess the feasibility and acceptance of the HRES system. In general, most of the authors consider four types of cost during assessing different economic indexes, namely Initial cost, operation, and maintenance cost, replacement cost, and fuel cost [1]. But in some literature, they also consider land buying and preparing costs, Labor costs [28], depreciation cost [1], carbon tax cost [29], salvage value [30], etc.

2.4 Technical Index

In literature, researchers have used different kinds of technical objectives, such as cover the load demand [35], increasing equipment lifetime [36], increasing system performance [37], system stability [38], increasing life time of storage system [36] etc.

2.5 Environmental Indices

One of the main reasons behind migrating from conventional power plant to renewable power plant is to reduce the environmental effect. This type of indexes is mainly used into multi objective optimization problem. Some common environmental index used in literature are carbon emission [12], Embodied energy [9], carbon footprint of energy [15], Life cycle assessment [24] etc.

2.6 Social Indices

Use of social index is not that popular among the research studies as renewable sources are still a growing sector. Still some authors use social indices in their literature review. Some common social indices we found investigating the literature are Human development index [16], job creation index [16], social acceptance [22], social cost of carbon [31] etc.

2.7 Optimization Techniques:

Jijan Lian et al. did an extensive review on optimization techniques used in the study of hybrid renewable optimization study [20] and mentioned three category of optimization techniques:

Type 1: Traditional methods

This type includes graphical construction, analytic method, iterative method, numerical and analytical method and probabilistic method [34]. This methods are basic , easy to understand and easy to use. But these take a long time to solve the problem and with the increase of decision variable complexity of the process increases and some times computers fail to handle them. Compared to the modern optimization algorithms these approaches fail to give the best answers.

Type 2: Artificial intelligence method:

AI methods broadly relate to the ability of robots or artificial products to perform similar duties to those of humans [38]. In HRES, mainly nature-based metaheuristic algorithms, heuristic algorithms, evolutionary algorithms, non-evolutionary algorithms, Fuzzy logic, and Neural network type algorithms are used. Some popular AI algorithms are PSO, genetic algorithm, ant colony algorithm, Bonobo algorithm, snake algorithm, simulated algorithm, INFO algorithm, Dandelion algorithm, pelican algorithm, simulated annealing algorithm and many more [23].

Type 3: Hybrid Method:

Hybrid methods are commonly developed from two or more AI algorithms to improve the quality of exploration and exploitation reducing the drawbacks of each algorithm. In recent years. a lot of hybrid methods are proposed by different authors, for example, GA-PSO, SA-CS (simulated annealing and chaotic search), CSHSSA (chaotic search, harmony search, and simulated annealing). HSSA (harmony search and simulated annealing), MOCSA (multi-objective crow search), and many more [39].

By studying the literature, we observe that researchers around the world have a growing interest in studying hybridizing different sources. As renewable sources are intermittent in nature researchers give great emphasis on energy security. Ensuring energy security during low weather resource time will require adding more sources which will waste more energy during peak weather resource time. Concern about reducing dump load is rare in the literature. Even if it is considered, considering dump load reduction and reliability simultaneously is not that common. Our study focuses on this.

Besides we observe people are not motivated enough in using CSP due to its high initial cost. So, we wanted to see if hybriding CSP with other sources can make an economical solution.

As the building of renewable sources is growing very fast, huge storage is required. Battery is the most common solution but for a bulk amount battery system is very costly and due to its low life span also creates huge environmental wastage. Keeping this in our mind, in our work we introduce thermal storage as the primary storage medium. The use of the thermal medium in CSP is common but in our design, we store energy from PV and WT also in thermal storage by the resistive heating concept.

Again, the growth rate of the field optimization algorithm is very high. Every week a new algorithm is proposed. But every algorithm has some good side and weak side and the feasibility of any optimization is problem specific. An algorithm good others' study may not be good for our study. So, we compare three types of recent optimization algorithms to find out which fits best for our problem.

CHAPTER 3

MATHEMATICAL MODELLING

3.1 Mathematical Modelling

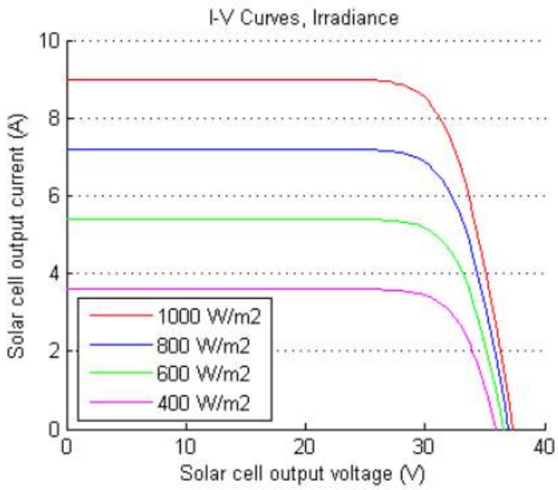
In this part of chapter, we discussed about the mathematical model of the components we used in this study. As our main objective is to use the model for observing the performance of different metaheuristic optimization algorithms, we do not go to the depth of the modeling and find a simplistic mathematical model of every component from the literature.

3.1.1 PV system

PV systems, which are primarily made of silicon, convert sunlight into electricity. Environmental factors, equipment, and system configuration all influence the performance of a solar farm. The following is a well-known formula for calculating the amount of power produced by a PV system.[1]

$$P_{pv} = \begin{cases} P_{rated}\left(\frac{DNI^2}{R_{standard} * R_{certain}}\right) & 0 \leq DNI < R_{certain} \quad (1) \\ P_{rated}\frac{DNI}{R_{standard}} & R_{certain} \leq DNI < R_{standard} \quad (2) \\ P_{rated} & otherwise \quad (3) \end{cases}$$

Where P_{rated} is rated power, $R_{certain}$ is certain radiation,$R_{standard}$ is standard solar radiation and DNI is the direct nominal irradiance.



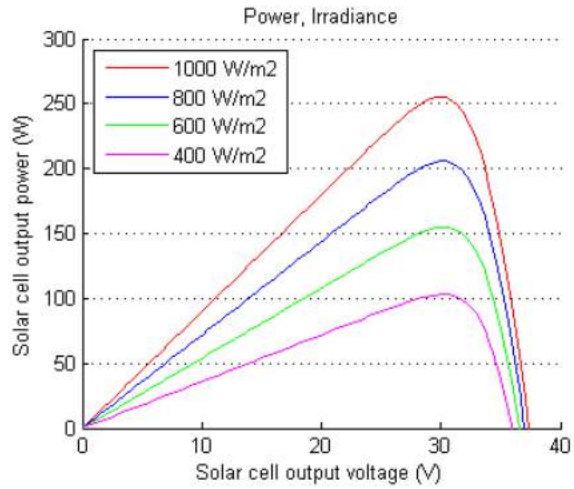


Fig 3.1: Typical I-V curve of a solar cell [31]   Fig 3.2: Typical power curve of a solar cell [31]

Figure 3.1 shows for a fixed irradiance how solar cell output current depends on the cell output voltage. fig 3.2 shows the dependency of output power with output voltage. For a specific voltage level solar cell gives the maximum power. All commercial solar cell tries to operate at this voltage level.

3.1.2 Wind Energy

A wind turbine is a device that converts wind kinetic energy into electrical energy. It is made up of several blades, a rotor, a shaft, a generator, and a tower. Wind blowing across the blades causes the rotor to turn, causing the generator to produce power. Wind turbines are available in a variety of sizes and configurations, ranging from small residential turbines to massive utility-scale turbines utilized in wind farms.

Following is a well-known equation to realize a wind turbine mathematically found in the literature.[31]

$$P_{wind} = 0 \qquad V_{speed} < V_{in} \;\; or \;\; V > V_{out} \tag{4}$$

$$P_{wind} = {V_{speed}}^3 \left(\frac{P_{rated}}{Vrated^3 - {V_{in}}^3}\right) - \left(\frac{{V_{in}}^3}{Vrated^3 - {V_{in}}^3}\right) P_{rated} \qquad V_{speed} > V_{in} and \; V_{speed} < V_{rated} \tag{5}$$

$$P_{wind} = P_{rated} \qquad V_{speed} > V_{rated} \text{ and } V_{speed} < V_{out} \tag{6}$$

Here, P_{rated} = rated power of the WT

V_{speed} = wind speed in that hour

V_{in}= minimum velocity of wind for which WT starts producing power

V_{out}= Maximum limit of wind speed that WT can withstood

V_{rated} = Rated speed of WT

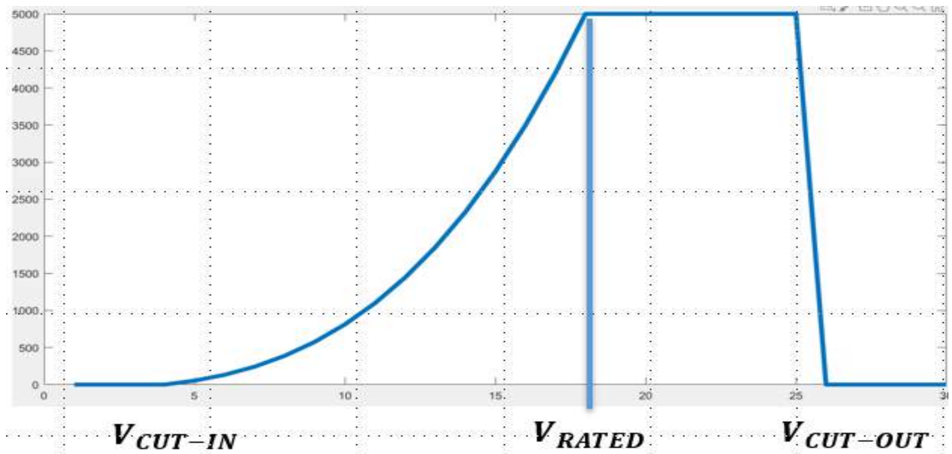


Fig 3.3: Output power curve of wind turbine

y-axis of this figure represents power output and x-axis represents wind velocity. This figure shows how power output of a wind turbine depends on wind velocity. From the graph we observe wind turbine does not starts produce power until a specific cut in wind velocity. After cut in wind velocity power output increases with the speed of wind. After wind speed reached to a rated velocity wind turbine produces maximum power and keep the power output constant. After a cut out velocity reached turbine is shut down for safety of the turbine.

3.1.3 Thermal Energy Storage (TES)

Thermal storage is coupled with CSP for more dispatchable and flexible operation of the energy system. In our study we replace battery with TES for less cost and less environmental effect. As we are only using TES in replace of battery, rather than going for technical details we have used a very simplistic black box model of TES. We assumed that the thermal storage tank is adiabatic in nature having no heat transferred to the environment [40]. When there is energy, the thermal storage medium increases its energy in a linear fashion.

During charge:

$$E_{thermal}\ (t+1) = E_{thermal}\ (t) + (\text{total renewable energy - load demand}) \tag{7}$$

During discharge:

$$E_{thermal}\ (t+1) = E_{thermal}\ (t) - (\text{load demand - total renewable energy}) \tag{8}$$

At each hour t, the capacity of TES is controlled by its minimum and maximum limit.

$$E_{thermal,min} < E_{thermal} < E_{thermal,max}$$

Where $E_{thermal,max}$ is a decision variable of our optimization problem and $E_{thermal.min}$ is 5% of $E_{thermal,max}$

As we are not using any battery so fluctuation of PV panel and wind are also captured by thermal storage. Electric to heat energy conversion efficiency has been taken as 100% [40]

3.1.4 Converter:

Rectifiers are necessary to convert alternating current to direct current, while inverters are required to convert direct current to alternating current. The mathematical model of the converter is as follows [32]:

For inverter, ac power = $n_{inverter}$ * dc power (9)

For rectifier, dc power = $n_{rectifier}$ * ac power (10)

$n_{inverter}$ and $n_{rectifier}$ are the efficiency of the inverter and rectifier respectively. Both is taken as 95% [33]

3.1.5 Fuel cell and storage system

The fuel cell in our study is used for the emergency backup solution. Though being a costly candidate, we replace the battery by fuel cell for a cleaner solution and so we are using it only for emergency cases in our study. PEMFC (proton exchange membrane fuel cell) has been chosen for their low operating temperature and pressure range, low weight and size, long life, no noise and GHG emission.[3]

The electrolyzer is used to produce H_2 from the excess energy of PV, CSP and Wind turbine.

Output power from Electrolyzer,

$$P_{electrolyzer} = P_{excess}(t) * \eta_{electrolyzer} \tag{11}$$

Here $\eta_{electrolyzer}$ is electrolyser efficiency and it is 85%. The saved energy in hydrogen at time step t is defined as

$$E_{Hydrogen}(t) = E_{Hydrogen}(t-1) + P_{electrolyzer} * del\ t \tag{12}$$

Here,

$$E_{Hydrogen-minimum} \leq E_{Hydrogen} \leq E_{Hydrogen-maximum}$$

The Ultra-Light Polymer Container with a hydrogen capacity of 2700 L is used here, and the tank's equivalent peak power volume is computed as follows

$E_{H2-max} = \frac{2700}{1000} * H_2\ heating\ valu[3]$

Heating value of $\boldsymbol{H_2}$ is 3.4 kwh/kg [3]. And

$$E_{H2-min} = 5\%\ of\ E_{H2-max}$$

3.1.6 CONCENTRATED SOLAR POWER(CSP)

In our study we have used a simple but complete model of solar tower type CSP model developed by CSTEP (Center for Study of Science, Technology and Policy), a private, nonprofit research corporation works with Governments and Institution to develop solutions using science and technology.[34]

A Solar Tower (ST) is a structure designed to reflect solar energy impinging on it onto a receiver at the top of a tower using a large number of heliostats or mirrors. The condensed solar energy striking the receiver is transmitted to a Heat Transfer Fluid (HTF) flowing through it.

The thermal energy of HTF is subsequently transmitted via a heat exchanger to a working fluid in the power block, resulting in the creation of electricity. ST systems often contain a storage component that allows for the storing of a portion of the solar energy captured for later usage (during nighttime/peak demand periods).

In contrast to the parabolic trough approach, the output energy is not proportional to the land area solar field. The amount of solar energy collected by ST is a complex function of the solar field arrangement, sun position, and tower height. Following subsections describes a simple and realistic means of calculating output energy. A step-by-step process of generating electrical energy from solar energy described below: [34]

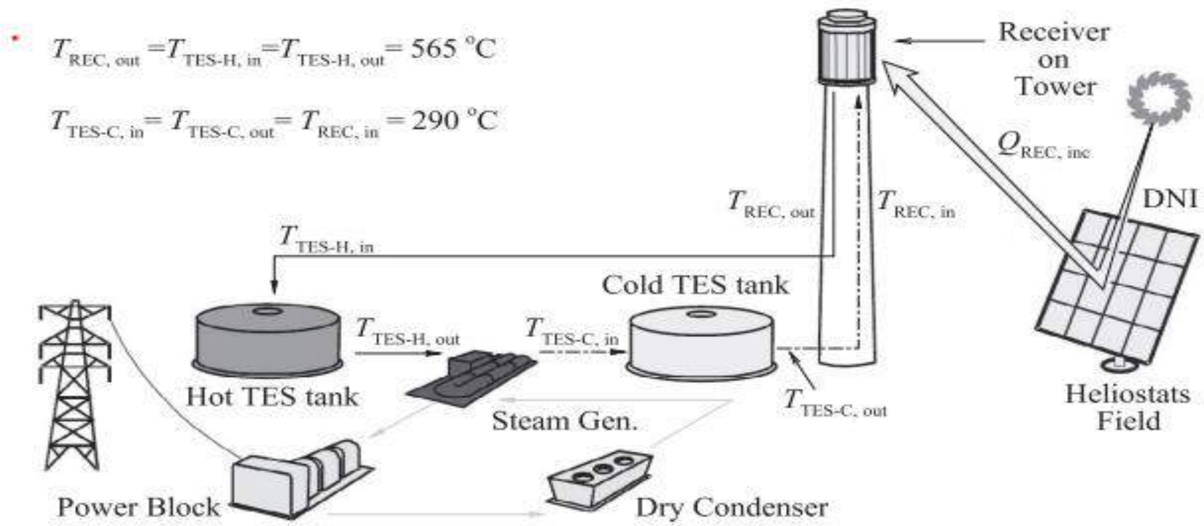


Fig: 3.4: A simple model of CSP. [10]

3.1.6.1 Solar field boundary and Number of field points within the boundary

For finding all the field points where we can place a heliostat first a solar field coordinate is developed. Where x axis and y axis distance are represented with respect to tower height. We are calling this non dimensional form of distance.

The x and y axes distance from the tower are defined as $\frac{a}{c}$ and $\frac{b}{c}$ respectively. The solar field was generated by progressively varying $\frac{a}{c}$ and $\frac{b}{c}$ from (-10, -10) to (10,10), with step increment of 0.25. Ultimately, the symmetrical boundaries of uniform annual solar energy per unit land area, e_l, were established.

$$e\_l = (Packing\_density) \sum_{t=0}^{8760} DNI_t * cos\theta_{t,x} \quad (13)$$

here, $cos\theta$ is the cosine loss, t is the hour of the year, x is the location of the point and DNI refers to the direct nominal irradiance which is collected from TMY weather data. The above equation consists of three terms. Among them, packing density and cosine loss need more discussion for its complexity to find their value. Thus, they are discussed in the next two sub-sections.

3.1.6.1.1 Cosine loss:

Cosine loss is a decrease in the actual reflection area of the heliostat due to the cosine of the incident angle of the sun. For ST type CSP, cosine effect is different for each of the heliostat depending on:

i. The geographical location of the plant (Latitude) for determining sun's position.
ii. The heliostats position
iii. The hour of the day

The process of calculating cosine effect for a heliostat is as follows:

a) $$Declination, delta = 23.45 * \sin\left\{\left(\frac{360}{365}\right) * (284 + p)\right\} \quad (14)$$

here p is the number of days in the year.

b) The hour angle is the angular displacement of the sun east or west of the local meridian caused by the earth's rotation on its axis at 15 per hour; morning is negative and afternoon is positive.

$$Hour\ Angle,\ omega = 15 * (q - 12) \quad (15)$$

Here q is the hour of the day ranging from 0 to 24.

c) The zenith angle is the angle between the vertical direction and a given direction, such as the direction of an object in the sky (here the sun). It is measured from the observer's zenith (the point directly overhead) to the object, with an angle of 0 degrees indicating an object directly overhead and 90 degrees indicating an object on the horizon.

$$Zenith\ Angle, theta = cos^{-1}\{(\cos(phi)\cos(delta) * \cos(omega)) + (\sin(phi)\sin(delta))\} \quad (16)$$

Where phi is the latitude of the location

d) $$Altitude\ angle, alpha = 90 - theta \quad (17)$$

e) $Azimuth\ angle\ , Azimuth\colon Azimuth' =$

$$cos^{-1}\left(\frac{sin(delta)cos(phi)-cos(delta)sin(phi)cos(omega)}{cos(alpha)}\right) \tag{18}$$

$$if\ \sin(omega) > 0, Azimuth = 360 - Azimuth', else\ Azimuth = Azimuth'$$

Finally, cosine angle is calculated as:

$$Cosine\ angle\ , = \frac{sin(alpha) - \frac{a}{c}cos(alpha)\sin(Azimuth) - \frac{b}{c}\cos(alpha)\,cos(Azimuth)}{\sqrt{1+\left(\frac{a}{c}\right)^2+\left(\frac{b}{c}\right)^2}} \tag{19}$$

$$\mathrm{Cos}(\theta_{t,x}) = \sqrt{\frac{1+\cos(2\theta_{t,x})}{2}} \tag{20}$$

(All angles are in degree)

The detailed derivation can be referred to in (Stine B William,2001).

3.1.6.1.2 Packing density:

Packing density is defined as the proportion of mirror area to land area. It illustrates how the heliostats are arranged in the specified area. A higher packing density indicates a smaller gap between two heliostats and a higher number of heliostats in the solar field, which results in an increase in power output and efficiency. However, to decrease shadowing and blocking loss and to ensure proper maintenance of mirrors, a specific gap between two heliostats is also required. In fact, the effect of blockage exponentially increases with radial distance from the tower.

So, the entire elemental area of a solar field does not reflect energy. Thus, it is crucial to consider the impact of packing density, the ratio of mirror area to land area, to determine the extent to which the elemental area is actually covered with a mirror. In different locations within the ST field, the value of packing density varies to minimize the effects of shadowing and blocking.

Value of packing density depends on the radial distance of a heliostat from the tower(y) and tower height (c) by the following expression.

$$Packing\ density = 0 \qquad \frac{y}{c} < \frac{y}{c_{minimum}} \tag{21}$$

$$Packing\ density = 0.492 - 0.0939\frac{y}{c} \qquad \frac{y}{c_{minimum}} \le \frac{y}{c} \le 2.8 \tag{22}$$

$$Packing\ density = \frac{0.6}{\sqrt{\left(\frac{y}{c}\right)^2 - 1}} \qquad \frac{y}{c} > 2.8 \tag{23}$$

For further information readers are encouraged to consult [34].

3.1.6.1.3 Solar Boundary

From the section 3.1.6.1 counters of fixed uniform annual solar energy per unit land area(e_l) was found. Now a contour value e_l=0.16 (KWh/m^2) is used to define the outer solar field boundary. Similar to the outer boundary there is a limit for the inner boundary as well. General trend in the existing plant is starting heliostat rows at a distance corresponding to half of the height of the tower that is $(\frac{r}{h})_{min} = 0.5$

Heliostats are arranged in radial staggered pattern in all the points between outer and inner boundary.

3.1.6.2 Design Solar Power ($P_{solar,design}$)

Required thermal energy of the heat transfer fluid (HTF) to generate design electric power which we will get from the optimization result, is,

$$P_{heat\_transfer\_fluid,design} = \frac{P_{capacity,design} * 10^3}{\eta_{power\_blockb} * \eta_{heat\_exchanger}} \tag{24}$$

Where $P_{capacity,design}$ refers to the design capacity in kW, η_{power_block} and $\eta_{heat\_exchenger}$ are power block and heat exchanger efficiency respectively.

Power block efficiency (η_{power_block}) is computed based on the following relation:

$$\eta_{power\_block} = 0.441 - 0.262 * e^{-0.06 * P_{capacity,design}} \qquad for\ 0 \leq P_{capacity,design} < 50 \tag{25}$$

$$\eta_{power\_block} = 0.44 \qquad for\ \ 50 \leq P_{capacity,design} \tag{26}$$

Required thermal energy to be collected from solar field is,

$$P_{solar,design} = \frac{P_{heat_{transfer_{fluid}},design}}{\eta_{rec}} \tag{27}$$

$$= \frac{P_{capacity,design} * 10^3}{\eta_{rec} * \eta_{power\_block} * \eta_{heat\_exchager}}$$

Here η_{rec} represents the efficiency of the receiver block.

3.1.6.3 Height of the Solar Tower:

For a small capacity plant (less than 1 MW) attenuation effects of the reflected rays were neglected and tower height for SM (solar multiple) =1 is calculated directly.

Solar power collected from the field in receiver for any hour, t is

$$P_t = ((\frac{da}{c} * \frac{db}{c}) * \text{row} * \sum_{k=1}^{N} DNI_t * \text{Cos}\big(\theta_{t,k}\big) * Packing\_Density) * height^2 \qquad (28)$$

Here N is the total field point and row is the reflectivity of the heliostats.

Now the task is to find the value of height, such that maximum of all 8760 P_t $values$

$$P_{tmaximum} = P_{solar,design}$$

Since it is an implicit equation, value of height will be found by iterative process.

$$\text{Height} = \sqrt{\frac{P_{solar,design}}{(\frac{da}{c} * \frac{db}{c}) * \text{row} * \sum_{k=1}^{N} DNI_t * \text{Cos}(\theta_{t,k}) * Packing\_Density)}} \qquad (29)$$

first a primary value is calculated for height by equation (29). If $P_{tmaximum}$ $value\ calculated\ with\ this\ height\ is\ less\ than$ $P_{solar,design}$ than height will be increased by 0.5 meter. In this way height will be increased until $P_{tmaximum}$ $is\ greater\ than$ $P_{solar,design}$.

3.1.6.4: Hourly Solar Power from the Field to the Heat Exchanger:

Actual power input to the heat exchanger is calculated by,

$$P_{heat\_transfer\_fluid,t} = ((\frac{da}{c} * \frac{db}{c}) * \text{row} * \eta_{rec} \sum_{k=1}^{N} DNI_t * \text{Cos}\big(\theta_{t,k}\big) * Packing\_Density) * height^2 \qquad (30)$$

3.1.6.5: Electric Energy Generated:

Total electric energy generated from the heat transfer fluid is,

$$P_{electrical,\,t} = P_{heat\_transfer\_fluid,t} * \eta_{power\_block} \qquad (31)$$

3.2 Energy Management Strategy

In this part of chapter, we discuss about our energy management strategy for this study. Energy management strategy controls the energy flow from source to the load and controls the charging and discharging of the storage system. That's why results of hybrid renewable energy optimization problem greatly vary with chosen energy management strategy.

Here we proposed an energy management strategy for maximizing solar energy with thermal energy storage as the primary storage medium, and hydrogen tank as the secondary storage medium, whereas fuel cell is being used for emergency cases only.

3.2.1 Proposed Energy Management Strategy

Scenario 1: Sufficient energy is generated by renewable sources (PV, WT, CSP) and the extra energy is used to charge the thermal energy storage (TES) that is stored in the form of heat energy

Scenario 2: Same as case 1 but the surplus energy is greater than the maximum limit of the TES. So, TES will store energy up to its maximum limit and rest of the energy will be used to energize electrolyzer to produce H_2 and store in H_2 tank.

Scenario 3: This is a continuation of scenario 2. The surplus energy crosses the max limit of TES and H_2 storage tank. Therefore, in this case, the surplus energy is consumed in a dump load.

Scenario 4: Energy supply by renewable sources falls short of the demand. Shortage of energy will be supplied by TES.

Scenario 5: Renewable energy and TES are not sufficient to meet the demand. In that case, fuel cell will take H_2 from hydrogen storage tank and produce electric energy.

Scenario 6: In the worst case, when renewable sources fail to meet the demand and both TES and hydrogen tank runs out of storage, loads will be unmet.

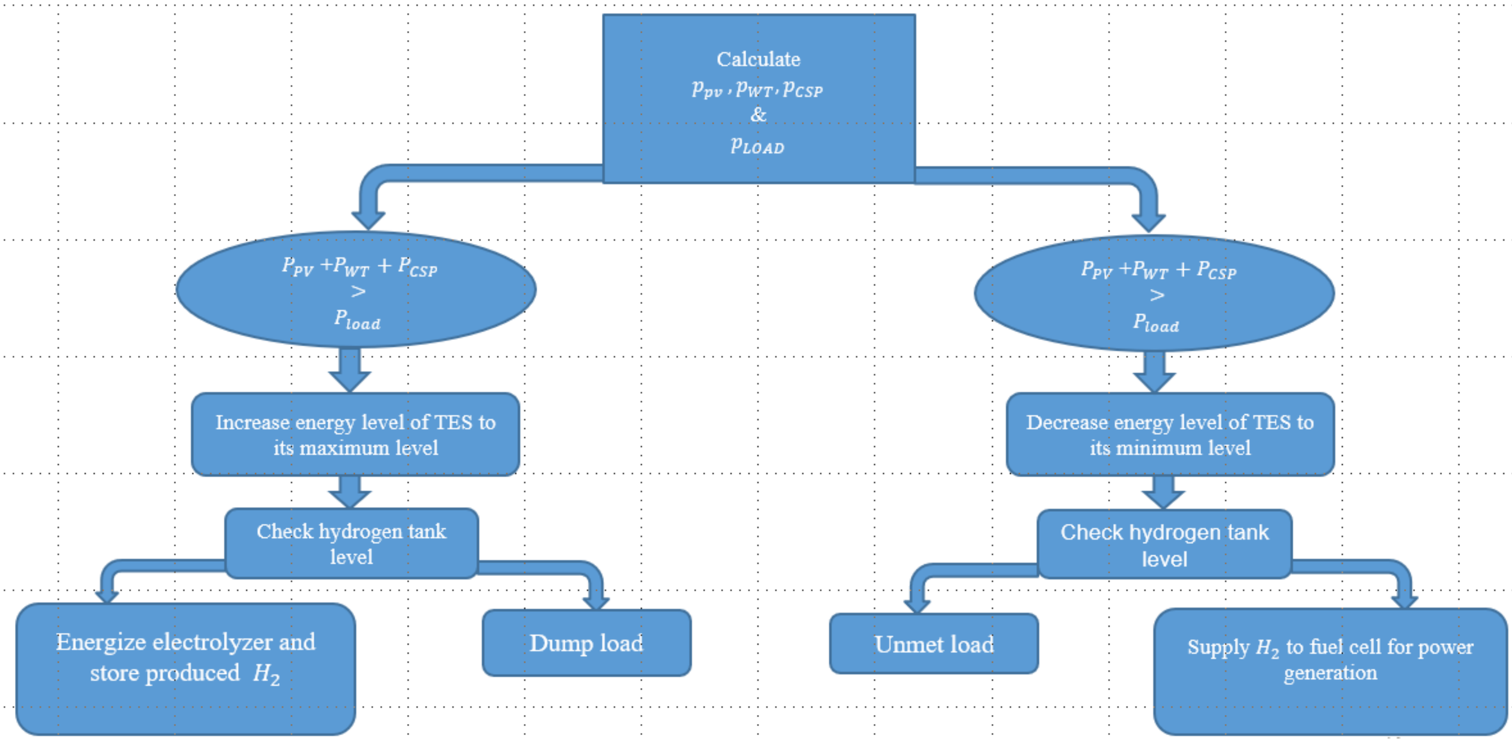


Fig:3.5: Proposed energy management strategy

3.3 Constraints

In this section we discuss about three constraints used in our study. First constraints are applied on the decision variable range to limit the search space for fast computation during optimization, the other two constrains are applied to ensure the energy security and efficient system design.

3.3.1 Decision variables and constraints

The decision variables used in our study are PV modules unit number, wind turbine unit number, CSP capacity, maximum storage capacity of hydrogen tank and storage capacity of thermal storage tank. The decision variables are ranging from a minimum and maximum value.

$$N_{PV,module,\ min} \leq N_{PV,module} \leq N_{PV,module,\ max}$$

$$N_{WT,unit,\ min} \leq N_{WT.unit} \leq N_{WT,unit,\ max}$$

$$P_{cap,\ d,\ min} \leq P_{cap,\ d} \leq P_{cap,\ d,\ max}$$

$$Ts_{min} \leq Ts \leq Ts_{max}$$

$$E\_h2\_min \leq E\_h2 \leq E\_h2\_max$$

Maximum and minimum value are set as 80 and 0. These limits are set to limit the solution space. Large solution space needs higher number of iterations to find out the best solution. Lower value of maximum limit increases unmet load and a higher value of maximum limit increases dump load. So, the limit is set at an early stage after running the optimization on trial-and-error basis.

3.3.2 System Reliability constraint

As renewable energy sources are completely weather dependent, there is a possibility that sometimes the model will be unable to satisfy the load demand. In this study, LPSP has been chosen as the reliability index. LPSP is defined as the loss of power supply probability.

$$LPSP = \frac{\sum_{t=0}^{T} time\ when\ load\ is\ unmeet}{T} = \frac{\sum_{t=0}^{T} Time(P_{available}(t)<P_{load}(t))}{T} \tag{32}$$

For calculating LPSP we need two types of data, available power generation from the model at that hour and load demand at that hour. Whenever load demand is higher than available power, that hour is taken as unmet hour. LPSP is the ratio of total unmet hour in a year to total hour in a year.

LPSP value varies between 0 and 1. LPSP = 0 means the system will supply power at all the time and LPSP = 1 means the system will never satisfy the load demand.

3.3.3 System Efficiency constraint

In hours when supply is higher than demand, we stored the extra energy for later use when the energy source is unavailable at night or in unfavorable weather condition. Capacity of the storage should be such that it is enough to supply the demand when renewable generation is low. So, the excess energy beyond storage capacity needs to be dumped. If we use more renewable sources for energy availability during low renewable production, excess energy will be produced during high renewable power production, which will be dumped. Dumping energy at a large scale indicates that our system is inefficient, wasting energy and renewable resources. So, we design a model that limits the total dump energy and balance between renewable source and storage capacity.

In this study, a new efficiency index DLP is used. DLP is defined as the Dump Load Probability.

$$DLP = \frac{\sum_{t=0}^{T} time\ when\ energy\ is\ dumped}{T} = \frac{\sum_{t=0}^{T} Time(P_{available}(t) > P_{load}(t))}{T} \quad (33)$$

For calculating DLP we need two types of data, available power generation from the model at that hour and load demand at that hour. Whenever load demand is lower than available power and the storage capacity is full, that hour is taken as dump hour.

3.4 Objective Function

In our study we use cost of energy (COE) as our objective function. Our main goal is to minimize total COE considering all three constraints. COE, which is the short form of cost of energy, can be described as the total cost per kWh generated energy. [31]

$$\text{COE} = \frac{TNPC}{Total\ generated\ energy\ in\ a\ year} \quad (34)$$

Here, TNPC is the total net present cost and it is calculated as the summation of net present cost (NPC) of all the component.

The following subsections discuss on the calculation of NPC of all the component used in this study.

3.4.1: PV Panel Cost

Net present cost (NPC) of the PV system, $NPC_{PV} = C_{Capital\ Invest,\ pv} + C_{OM,\ npv}$ (35)

Here,

Capital investment cost,

$$C_{Capital\ investI,\ pv} = N_{pv} * pr_{pv} \quad (36)$$

Yearly operation and maintenance cost,

$$C_{OM,\ npv} = C_{OM,\ pv} * N_{pv} * \sum_{n=1}^{N} \left(\frac{1+E}{1+r}\right)^{n} \quad (37)$$

Where pr_{pv} is price of one PV panel and $C_{OM,\ pv}$ is yearly operation and maintenance cost of one

PV panel. Inflation (F), escalation (E) and interest rates (r) are economical parameters used to increase the accuracy of the calculation. Life span of PV panel in our study is 20 years.[1]

3.4.2: Inverter cost

Net present cost (NPC) of the inverter system, $NPC_{PV} = C_{Capital\ investI,\ inv} + C_{OM,\ ninv} + C_{RE,\ ninv}$ (37)

Here,

Capital investment cost,

$$C_{Capital\ investI,\ pv} = pr_{\ inv} * P_{inv} \tag{38}$$

Yearly operation and maintenance cost,

$$C_{OM,\ ninv} = C_{OM,\ inv} * N_{inv} * \sum_{n=1}^{N} \left(\frac{1+E}{1+r}\right)^{n} \tag{39}$$

Replacement cost,

$$C_{Replacement,\ ninv} = pr_{inv} * P_{inv} * \left(\frac{1+F}{1+r}\right)^{nl} \tag{40}$$

Where pr_{inv} is price of inverter per Kw, nl is the life span of inverter (10 years for our study) and P_{inv} is the power rating of inverter which depends on the maximum power of PV and FC system.

3.4.3: Wind Turbine Cost

Net present cost (NPC) of the wind turbine system, $NPC_{WT} = C_{Capital\ investI,\ WT} + C_{OM,\ nwt}$ (41)

Here,

Capital investment cost,

$$C_{Capital\ investI,\ WT} = N_{wt} * pr_{wt} \tag{42}$$

Yearly operation and maintenance cost,

$$C_{OM,\ nwt} = C_{OM,\ wt} * N_{wt} * \sum_{n=1}^{N} \left(\frac{1+E}{1+r}\right)^{n} \tag{43}$$

Where pr_{wt} is price of one WT and $C_{OM,\ WT}$ is yearly operation and maintenance cost of one wind turbine.

Life span of wind turbine in our study is 20 years.[31]

3.4.4: Fuel Cell system cost

3.4.4.1: Fuel cell

Net present cost (NPC) of the fuel cell, $NPC_{PV} = C_{Capital\ investI,\ fc} + C_{OM,\ nfc} + C_{Replacement,\ nfc}$ (44)

Here,

capital investment cost,

$$C_{Capital\ investI,\ fc} = pr_{\ fc} * N_{fc} \tag{45}$$

Yearly operation and maintenance cost,

$$C_{OM,\ nfc} = C_{OM,\ pv} * N_{fc} * \sum_{n=1}^{N}\left(\frac{1+E}{1+r}\right)^{n} \tag{46}$$

Replacement cost,

$$C_{Replacement,\ nfc} = C_{RE,\ fc} * N_{fc} * \sum_{n=5,10,15}\left(\frac{1+F}{1+r}\right)^{n} \tag{47}$$

Here, pr_{fc} is FC price of one cell and N_{fc} is total number of this kind fuel cell. Normally life span of a proton exchange membrane fuel cell is more than 400000 hours. So, in 20 years of project time this needs to replace approximately 3 times.

3.4.4.2: Electrolyser:

Net present cost of electrolyser, $NPC_{elec} = C_{Capital\ investI,\ elec} + C_{OM,\ nelec} + C_{Replacement,\ nelec}$ (48)

Here,

capital investment cost,

$$C_{Capital\ investI} = pr_{\ elec} * P_{elec} \tag{49}$$

Yearly operation and maintenance cost,

$$C_{OM,\ nelec} = C_{OM,\ elec} * P_{elec} * \sum_{n=1}^{N}\left(\frac{1+E}{1+r}\right)^{n} \tag{50}$$

Replacement cost,

$$C_{Replacement,\ nelec} = pr_{elec} * P_{elec} * \left(\frac{1+F}{1+r}\right)^{nl} \tag{51}$$

Where pr_{elec} is price of inverter per Kw, nl is the life span of inverter (10 years for our study) and P_{elec} is the power rating of electrolyser which depends on the maximum storage capacity of hydrogen storage capacity.

3.4.4.3: Hydrogen Tank:

Net present cost (NPC) of the Hydrogen tank, $NPC_{hst} = C_{Capital\ investI,\ hst} + C_{OM,\ hst}$ (52)

Here,

capital investment cost,

$$C_{Capital\ investI,\ WT} = P_{hst} * pr_{hst} \tag{53}$$

Yearly operation and maintenance cost,

$$C_{OM,\ hst} = C_{OM,\ hst} * P_{hst} * \sum_{n=1}^{N}\left(\frac{1+E}{1+r}\right)^{n} \tag{54}$$

Where pr_{hst} is price of per kg of storage capacity and P_{hst} is the kg equivalent of the maximum energy storage capacity of hydrogen tank.

3.4.5: CSP and Thermal Storage Cost

Net present cost (NPC) of CSP and TES, $NPC_{csp} = C_{Capital\ investI,\ csp} + C_{OM,\ csp}$ (55)

Capital investment cost,

$$C_{Capital\ investI,\ csp} = C_{HF} + C_{T\&R} + C_{TES} + C_{BOP} + C_{PC} \qquad (56)$$

C_{HF} = Heliostat field cost

$C_{T\&R}$ = tower and receiver cost

C_{TES} = thermal storage

C_{BOP} = Balance of plant cost

C_{PC} = Power cycle cost

Yearly operation and maintenance cost,

$$C_{OM,\ csp} = C_{cap,\ CSP} * C_{cap,\ CSP} * \sum_{n=1}^{N} \left(\frac{1+E}{1+r}\right)^{n} \qquad (57)$$

$C_{cap,\ CSP}$ = Fixed cost

$C_{cap,\ CSP}$ = Variable cost

CHAPTER 4

OPTIMIZATION ALGORITHM

In our study we apply 3 optimization algorithm and compare their result. A short discussion about the algorithms is described in this chapter.

4.1 Particle swarm optimization:

Particle swarm optimization (PSO) is an algorithm where collective behavior of swarms are employed to explore a variable dimensional space and obtain an optimal solution output [11].

PSO operates on two major grounds the positions and velocities of particles. It iterates these two factors of swarm to obtain personal best and global best. In every iteration the velocity update equation adjusts the Personal best that moves towards the Global best which allows effective exploration of space.The new positions after update uses an objective function as baseline, when the particle improves the PBS contributes to GBS ad recuring iterations are also memorized.

Iterative process continues till a termination condition that is predefined by number of iterations or upon the arrival of a satisfactory range of solution. [36]

Algorithm:

```
For each particle
        Initialize particle
End for
Do
        For each particle
Calculate fitness value
If the fitness value is better than the best fitness value in history set current value as the new
personal best

End
Chose the particle with the best fitness value of all the particles
For each particle calculate velocity
Velocity= inertial constant + exploration constant * random variable (0-1) * (personal best –
current position) + exploitation constant * random variable (0-1) * (global best –   current
position)

and update the position
Updated position = previous position + velocity

End
While maximum iteration or minimum error criteria is not attained
```

4.2 Dandelion optimization algorithm (DO):

An optimization method called the Dandelion algorithm takes its cues from dendritic networks. It creates a population of potential solutions known as dendrites, which develop and change according to predetermined rules. The dendrites balance exploration and exploitation as they traverse a vast search space through cooperation and information sharing. Dandelion has demonstrated potential in the solution of challenging nonlinear problems. Termination criteria are used to determine its convergence, and it has been successfully used in a number of areas. Overall, by emulating dendritic development and interaction patterns, Dandelion provides an effective and efficient optimization strategy. [37]

1. Initialization

DA generates A dandelions at random inside the search area.

2. Normal Sowing

Within a specific sowing radius, each dandelions produces dandelions seeds. The more seeds are produced the lesser the fitness value. The quantity of seeds is determined through this and hence radius is varied. Additionally, different dandelions have varying sowing radii that will be determined using different methods that will be explained later.

3. Mutation Sowing

A local optimum is jumped out of using Levy mutation applied to the algorithm to lowest fitness called best dandelion.

4. Selection process

Using a disruptive selection operator, new A-1 dandelions are selected from the remaining ones. Following the initial step, normal sowing, mutant seeding, and selection are done to satisfy the requirements.

Algorithm:

Generation of normal seeds:

```
Input: Ai
Output: All Fi
For i = 1 to Ai do
        Set a = rand (1,d)
        For x = 1 to d do
                If x ∈ z then
                        If  F(x,i) as best
                        F(x,i) = F(x,i) + rand (0,Rbd)
                        Else
                        F(x,i) = F(x,i) + rand (0,Ri)
                        End if
                        If F(x,i) out
                         generates a location in the search space randomly
                        End if
                    End if
                  End if
                End if
```

Generating of mutation seeds:

```
Input: Am
Output: All Fi
For i = 1 to Am do
  Set a = rand(1,d)
  For b = 1 to d do
        If b ∈ z then
          Produce mutation seeds Fbd
          If Fbd out of bounds then
          Randomly generate a location in the search space
End if
    End if
        End if
      End if
```

In conclusion, the Dandelion algorithm uses dendritic development to solve challenging optimization issues. Dandelion presents a distinct and efficient optimization technique with the potential for applications across numerous areas by constantly developing and adapting dendrites, exchanging information, and balancing exploration and exploitation.

4.3 Pelican Optimization Algorithm (POA):

The Pelican Optimization method (POA) is a naturalistic optimization method inspired by pelicans' foraging patterns. It was suggested as an optimization problem-solving metaheuristic algorithm. The program, which was motivated by the cooperative behavior and successful hunting strategies of pelicans, aims to find the best solutions by balancing exploration and exploitation. [38]

The POA follows a set of steps to search for the best solution:

1. Initialization: Create a population of potential answers, symbolized by pelicans, at random in the search field.

2. Assessment: Measure each pelican's suitability as an answer to the optimization issue to determine its fitness.

3. Movement: Global movement, local movement, and exploratory movement are the three different forms of movement that pelicans engage in. Global mobility entails shifting the pelican's posture to reflect the current best answer. Exploiting prospective locations close to the pelican's current location is the goal of local movement. New areas of the search space can be explored more easily when there is exploratory movement.

4. Updating: After the movement phase, update the positions and fitness of the pelicans based on the movement rules and the evaluation of the new solutions.

5. Verify whether a termination requirement has been satisfied, such as completing the required number of iterations or arriving at a satisfactory solution. Exit the loop if the condition is true; otherwise, repeat steps 2 through 4.

6. Output: Output the pelicans' best solution, which is an ideal or nearly ideal solution to the problem, when the algorithm has finished.

Pseudo algorithm for POA:

Initialize the problem

Set population size(S) and total iteration(X)
Initialize the position and calculate cost function.
For t = 1:X
Produce random pray position.
For I = 1:S
Phase 1: Approaching prey
For j = 1: a
Determine the updated status of the jth dimension.
End.
Update the ith population member
Phase 2: Floating on the water's surface
For j = 1: a
Determine the updated status of the jth dimension.
End.
Determine the updated status of the ith dimension.
End.

Determine best solution
End.

It's vital to keep in mind that precise mathematical formulations or equations related to the Pelican Optimization Algorithm may change based on how they are used or modified by different scholars.

CHAPTER 5

Results and Discussion

5.1 Simulation Data

Technical and economic data:

Table 5.1: PV parameters used in this study [1]

Parameter name	Description	Value
PV lifespan	Useful life of PV panel	20 years
Prated	Nominal power of PV panel	260 W
$R_{standard}$	Standard solar radiation	1000 W/m^2
$R_{certain}$	Certain radiation	150 W/m^2
pr_{pv}	Price of one PV panel	468 $/panel
$C_{OM,\ pv}$	Operation and maintenance of one PV panel	2% of capital cost

Table 5.2: WT parameters used in this study [31]

Parameter name	Description	Value
WT lifespan	Useful life of WT	20 years
Prated	Rated power of WT	5000 W
V_{in}	Minimum wind speed to start electricity generation	4 m/s^2
V_{out}	Maximum wind speed for safe operation	25 m/s^2
V_{rated}	Nominal wind speed	18 m/s^2

pr_{pv}	Price of one WT	3000 $
$C_{OM, pv}$	O.M. cost one PV panel	2% of capital cost

Table 5.3: Inverter parameters used in this study [1]

Parameter name	**Description**	**Value**
Inverter lifespan	Useful life of inverter	10 years
η_{inv}	Efficiency of inverter	95%
pr_{inv}	Price of inverter for per KW	100$/kw

Table 5.4: Fuel cell parameters used in this study [1]

Parameter name	**Description**	**Value**
FC life span	Average life span of a PEM type fuel cell	5 years
Electrolyser lifespan	Average life span of a Elctrolyser	15 years
Hydrogen tank lifespan	Average life span of a hydrogen tank	20 years
η_{fc}	Fuel cell efficiency	50%
η_{elz}	Electrolyser efficiency	85%
η_{inv}	Hydrogen tank efficiency	
pr_{fc}	Capital cost of fuel cell per kw	3000 $/kw
pr_{elec}	Capital cost electrolyzer per kw	2000 $/kw
pr_{hst}	Capital cost hydrogen tank per kw	660 $/kg
$C_{OM, fc}$	O.M. cost of fuel cell	2 % of capital cost

$C_{OM, elez}$	O.M. cost of electrolyzer	20 $
$C_{OM,hst}$	O.M cost of hydrogen storage tank	2 % of capital cost
$C_{RE, fc}$	Replacement cost of fuel cell	2500 $/kw
$C_{RE, elz}$	Replacement cost of electrolyser	1500 $/kw

Table 5.5: CSP and TES parameters used in this study [35]

Parameter name	**Description**	**Value**
C_{HF}	Heliostat field cost	145 $\$/m^2$
$C_{T\&R}$	Tower and receiver cost	200 $/kw(thermal)
C_{TES}	Thermal storage cost	24 $/kwh
C_{BOP}	Balance of plant cost	340 $/kw(electrical)
C_{PC}	Power cycle cost	1100 $/kw(electrical)
$C_{cap, CSP}$	Fixed cost	66 $/kw-yr
$C_{gen, CSP}$	Variable cost	3.5 $/MWh
Φ	Latitude of location in degree	23.8103 N
ρ	Reflectivity of heliostat	85%
η_{rec}	Receiver efficiency	90%
$\eta_{heatexchanger}$	Heat exchanger efficiency	70%
η_{st}	Thermal storage efficiency	95%

Table 5.6: Common parameters [1]

Variable name	**Description**	**Value**
N	life time	20 years
E	Escalation rate	4%
F	Inflation rate	9%
r	Interest rate	10%

Load Data:

This load data is the hourly load demand of Board bazar, Gazipur, a city of Bangladesh. We used a scaled version of this data as our study is for an proposed hybrid power plant. This data is collected from the local source PGCB.

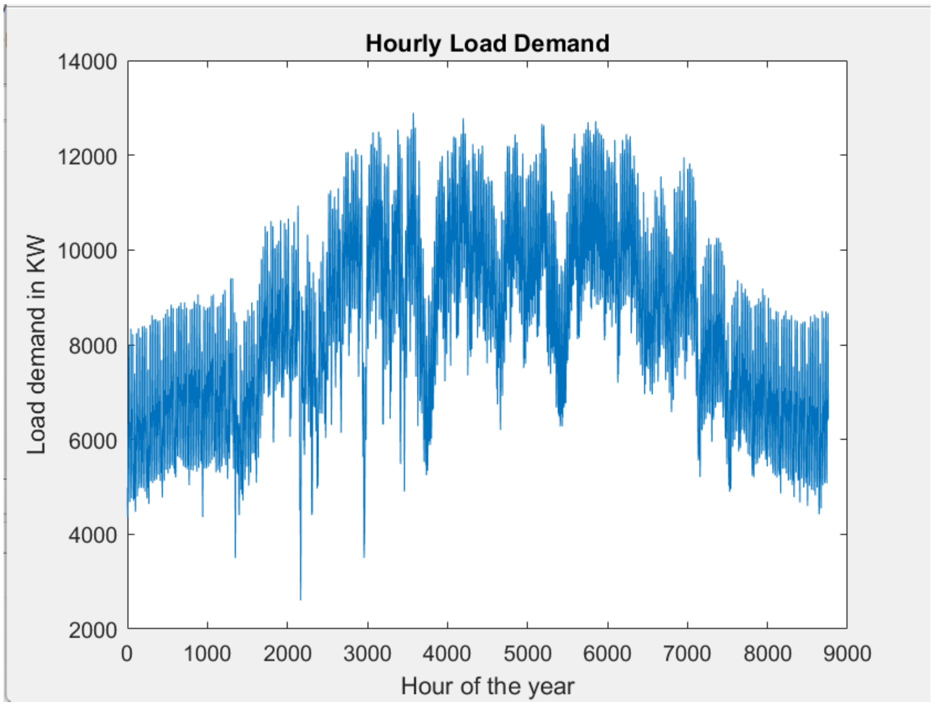


Fig:5.1: Hourly demand for a year

Environmental data:

Environmental data are collected from PVGIS-SARAH database for a location latitude 23.945(decimal degree) and longitude 90.383 (decimal degree).

Hourly Wind Speed

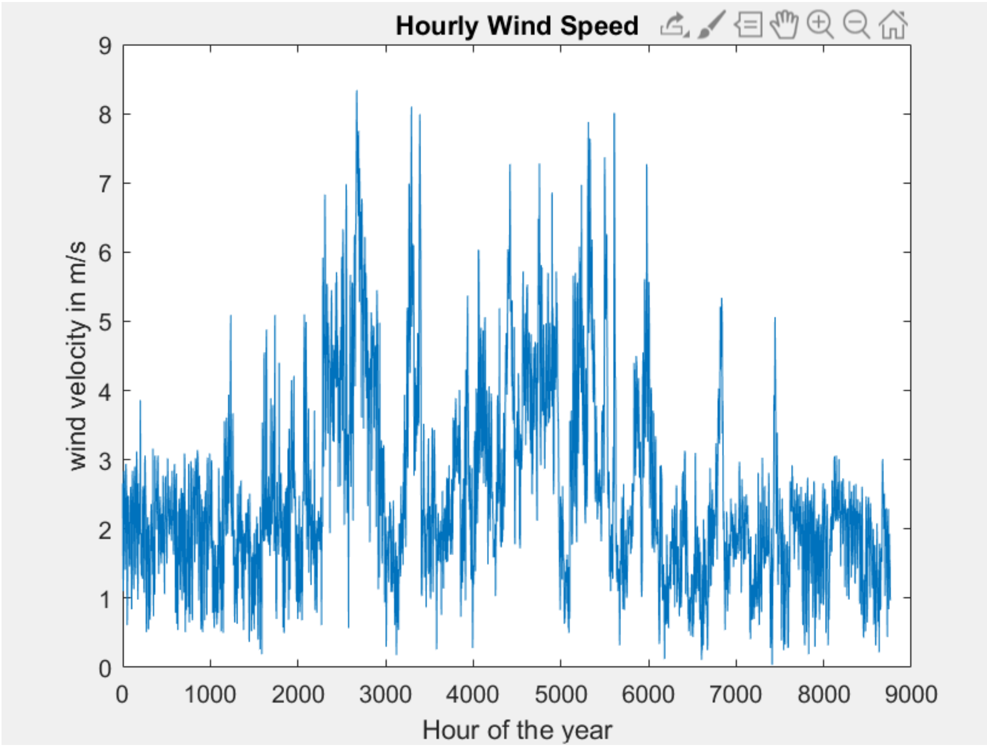


Fig:5.2: Hourly wind speed

Hourly Solar Radiation (W/m^2):

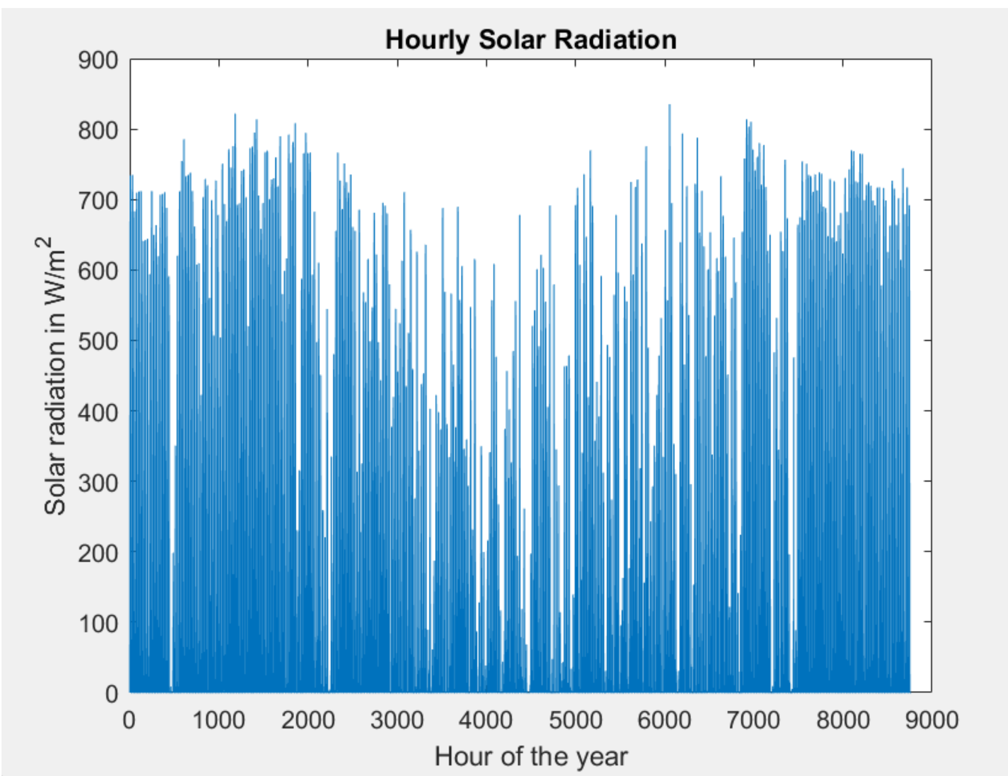


Fig:5.3: Hourly solar radiation

Hourly Ambient Temperature

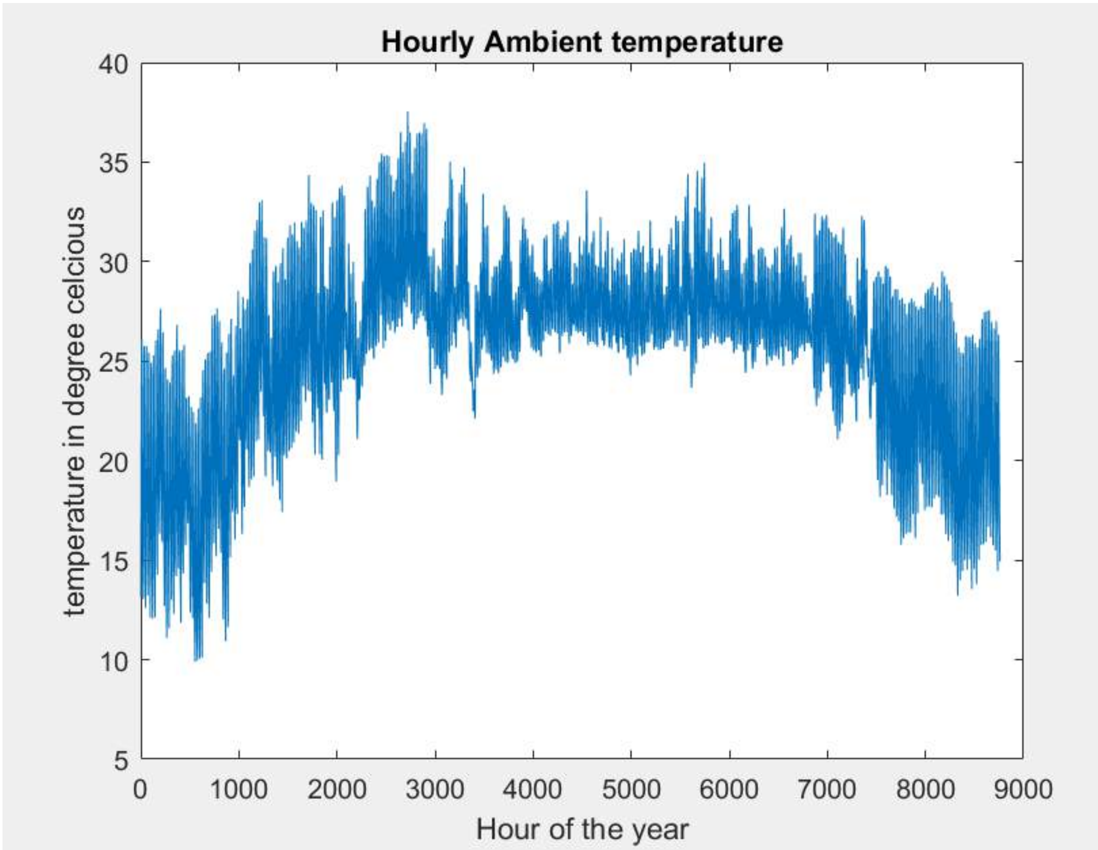


Fig:5.4: Hourly ambient temperature

Our results are divided into 2 sections, computation speed of the algorithm and comparison between the cost of energy from the 3 optimization processes that we used.

5.2 Results

5.2.1 Findings of computation speed

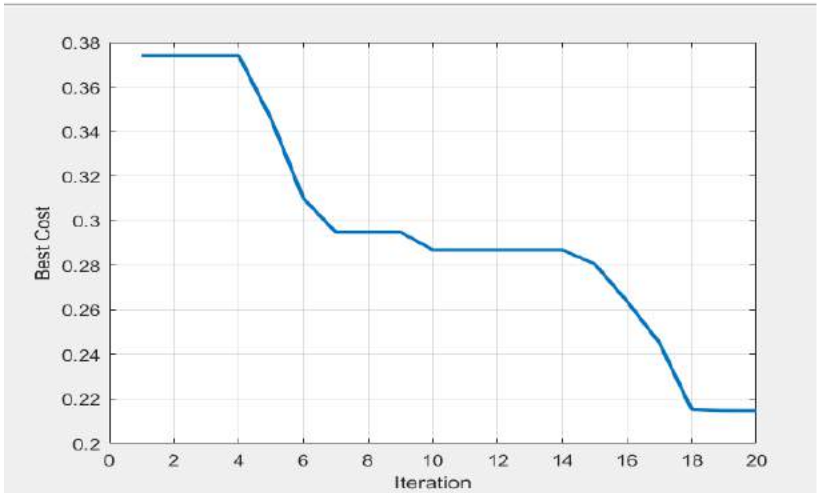


Fig 5.5: Convergence curve of particle swarm optimization

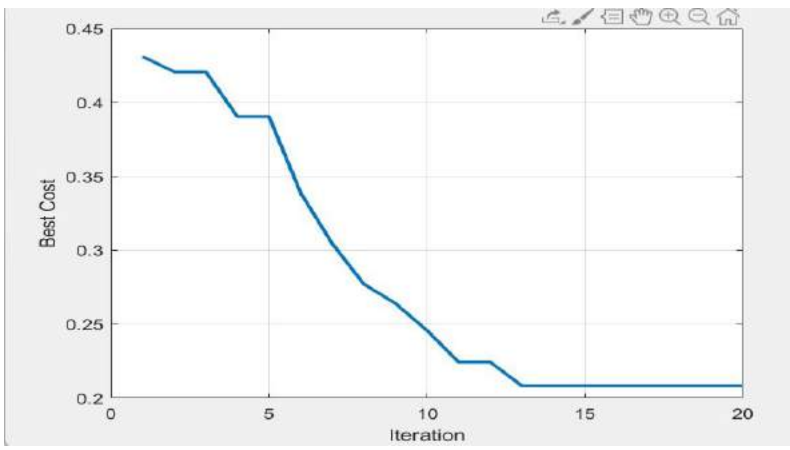


Fig 5.6: Convergence graph of Pelican optimization algorithm

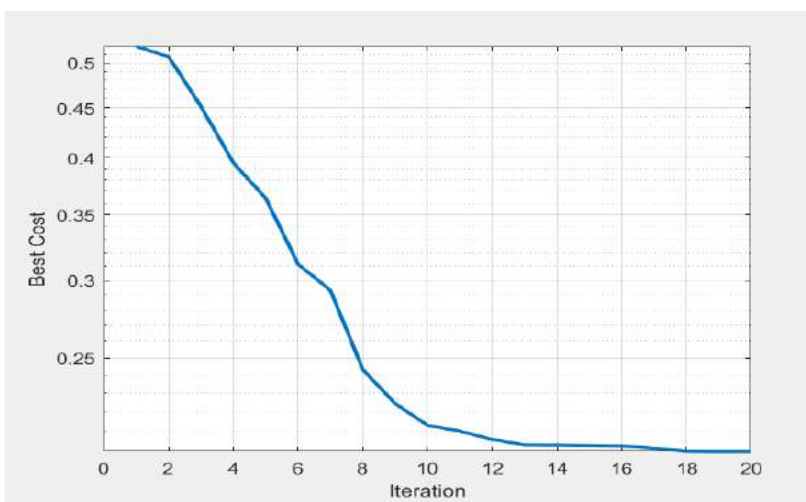


Fig 5.7: Convergence graph of Dandelion Optimization

The convergence curve is obtained to determine which optimization technique provides better output when subjected to the number of iterations. More the number of iterations the techniques require to converge, better output is obtained from the 3 graphs we can see that DO require the most number of iterations and DO also provides the best COE which is shown in the next section.

5.2.1: Cost of energy

Optimization Algorithm	LPSP	DLP	Population Size	Iteration	No Of PV	No Of WT	Capacity of CSP(kW)	Thermal Storage Hour	Storage Capacity of Hydrogen tank	COE ($/kWh)
PSO	5%	10%	25	20	9	4	73	12	0.02314	0.2084
DO	5%	10%	25	20	48	2	66.2	13	0	0.2007
PO	5%	10%	25	20	5	2	78.59	16	0.0416	0.21477

Table 5.7: Result of COE

For comparing the result of three optimization algorithm, we kept the LPSP, DLP, Population size and Iteration's constant. Population size is taken as 25 and iteration number 20. We are allowing 5% LPSP and 10% DLP for our analysis. After our simulation, we can see that the cost of energy for DO is the least among all three-optimization algorithm. From the table, the best configuration of the hybrid renewable energy system is 48 unit of PV panel, only 2 WT, 66.2 KW design capacity of CSP, 13 hours of thermal storage and zero hydrogen tank storage.

From the three results we observe a common fact that all three algorithms emphasize more on the use of solar resource and less wind resource. This is mainly for two reasons; capital cost of WT is higher than PV panel and average wind speed in our studied location (Gazipur) is not that significant. And another observation is though being a clean and promising source having a number of advantages, Fuel cell is neglected by the optimizer due to its very high cost.

5.3 Discussion

The outcome of this study interprets that making a reliable system with 100% system is possible. Besides Hybriding CSP with other type of sources can reduce the cost of energy. How ever extensive research needs to be done in reducing the cost of fuel cell otherwise it cannot be chosen as a possible solution though having lots of positive prospects. Again, reducing dump energy does not mean it will be less reliable. Making a cost-effective reliable solution reducing the dump energy is possible. Choice of best algorithm for an optimization problem varies with our preference, do we want fast computation or best result. However, the results should be interpreted with caution due to the limitation of the current research. The main limitations of this study are high computation time. For this reason, we iterate for small iteration number. The result of metaheuristic algorithms varies so much. So, this may be a problem. Again, made a lot of assumption that is for ideal case for example 100% resistive heating efficiency, does not consider attenuation effect of solar energy, does not consider wind turbine height, took all the economic parameter from the literature.

CHAPTER 6

Conclusion

In this work we used three different metaheuristic optimization algorithms to compare their feasibility and find the best possible configuration of PV/WT/CSP/TES/HFC based hybrid system. Comparing the literature this configuration gives a low-cost solution (COE of 0.2007 $/kwh) using 48 unit of PV panel, only 2 WT, 66.2 kw design capacity of CSP, 13 hours of thermal storage and zero hydrogen fuel cell considering 10% dump load time and only 5% energy loss time. According to the study, for this PV/WT/CSP/TES/HFC configuration PO works faster than other two algorithm but DO gives the best result in term of cost of energy.

In future we want to introduce multi-objective optimization into our system. This will enable us to simultaneously optimize multiple objectives, such as maximizing renewable energy generation, minimizing costs, and reducing environmental impacts. Consideration of multiple objectives will yield the best trade-offs and solutions that balance various factors.

We aim to conduct a comprehensive life cycle assessment of our system We will investigate and assess the environmental implications associated with our energy system's complete life cycle, from raw material extraction and production to operation and disposal, and find opportunities for improvement. Further enhancements can be made to reduce the environmental impact of our system. Load uncertainty is another factor we will address in our future plans. We will incorporate load uncertainty models and advanced forecasting techniques to better predict and manage fluctuations in demand. By improving load forecasting accuracy, we can optimize the system's performance and enhance its reliability in dynamically changing conditions.

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