Design and Economic Analysis of a Standalone Hybrid Renewable Energy System using Grey Wolf Optimizer

A PROJECT REPORT

Submitted in partial fulfilment of the requirements for the degree of

BACHELOR OF TECHNOLOGY

In

ELECTRICAL AND ELECTRONICS ENGINEERING

By

Yandra Mohith Sai (18BEE0255)

Kunal Chandra (18BEE0246)

Under the Guidance of

Prof. Jayabarathi T

SCHOOL OF ELECTRICAL ENGINEERING

VIT Vellore

VELLORE – 632014, Tamil Nadu, India

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DECLARATION

I hereby declare that the thesis entitled **"Design and Economic Analysis of a standalone Hybrid Renewable Energy System using Grey Wolf Optimizer"** submitted by me, for the award of the degree of Bachelor of Technology to VIT, Vellore is a record of Bonafede work done under the supervision of Prof. Jayabarathi T.

I further declare that the work reported in this thesis has not been submitted and will not be submitted, either in part or in full, for the award of any other degree or diploma in this institution or any other institution or university.

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CERTIFICATE

This is to certify that the thesis entitled **"Design and Economic Analysis of a standalone Hybrid Renewable Energy System using Grey Wolf Optimizer"** submitted by Yandra Mohith Sai (18BEE0255) and Kunal Chandra (18BEE0246), School of Electrical Engineering, VIT, Vellore, for the award of the degree of Bachelor of Technology in Electrical and Electronics Engineering, in a record of Bonafede work carried out by him under my supervision, as per the VIT code of academic and research ethics.

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Dean

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Yandra Mohith Sai

Kunal Chandra

Executive Summary

Connecting to the grid to generate electricity in isolated, distant rural places is typically too expensive. Renewable energy sources (RESs) present a great potential for meeting the basic electricity demands of remote and isolated places. Microgrids based on renewable energy (RE) are the most suited and cost-effective solution for electrifying off-grid areas.

Main challenges for hybrid renewable energy system (HRES) are planning and optimal design of such system from a technical and economic stand point. The proper scaling of a HRES is a crucial stage in its design. As long as the cost of capital equipment is a significant factor in the price of renewable energy an efficient framework is required for the use of off-grid hybrid systems (PV-WT-DG-Battery).

This Project aims on the application of latest naturally – inspired metaheuristic optimization algorithm named Grey Wolf optimizer (GWO) which is inspired from grey wolfs. The GWO algorithm is modelled after the natural leadership structure and hunting mechanism of grey wolves. The proposed algorithm is applied to determine the optimal system configuration and minimize the cost of power generation system in remote area. Further, GWO's effectiveness in solving the optimization problem is evaluated, and its performance is compared to that of other meta-heuristic algorithms (PSO, CS and GOA). The simulation results show that GWO is able to optimally size the system easily with fast convergence and lower system capital cost as compared to other meta-heuristic algorithms and HOMER.

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List of Abbreviations

α_t	Temperature Coefficient
σ	Self-Discharge rate of the battery
q	fuel consumption
B_{cap}	Battery Capacity
E_b	Energy stored in the battery
E_{bmin}	Minimum energy stored in the battery
E_{bmax}	Maximum energy stored in the battery
E_{ch}	Battery charging
E_{dch}	Battery discharging
E_{dump}	Dump energy
η_B	Battery efficiency
η_{inv}	Inverter efficiency
G_t	Solar irradiance
h	Wind turbine hub height
h_{ref}	Wind turbine reference height
β	Power law exponential
P_{dch}	Battery power Discharge
T_{ref}	Temperature at standard test condition
P_l	Energy demand
P_{pv}	PV power
P_{wt}	Wind-turbine output power
P_{ch}	Excess power charging battery

P_r	Wind turbine rated power
T_{amb}	Ambient temperature
V	Wind speed
$V_{cut\text{-}in}$	Cut-in speed
$V_{cut\text{-}out}$	Cut-out speed
V_{rated}	Nominal wind speed
V^h	Wind speed at hub height
V^{ref}	Wind speed at reference height
F	Fuel consumption
AD	Autonomy Day
PV	Photovoltaic panel
DG	Diesel Generator
WT	Wind turbine
DPSP	Deficiency of power supply probability
COE	Cost of energy
LPSP	Loss of power supply probability
LCC	Life cycle cost
CRF	Capital recovery factor
ACS	Annualized cost of a system
GWO	Grey wolf optimizer

Chapter 1

Introduction

Hybrid renewable energy system (HRES) are the most reliable and cost-effective way for electrifying the remote areas. However, from an economic and technical standpoint, the planning and optimal sizing of such a system is challenging due to various factors. For instance, the inconsistency of RE sources and their reliance on weather patterns. Generally, microgrids are either oversized or undersized to meet the load demand. Oversizing a system will result in high system cost and the production of the excess energy. Furthermore, an undersized microgrid system will result in power supply failure to the intended loads. In order to overcome the aforementioned challenges, proper scaling of a microgrid is crucial.

The latitude and longitude for the specified site are 12°54'59.46" N and 79°7'56.99" E. Because of its hot climate conditions, Vellore has a large potential for solar power generation. The solar radiation and wind speed for the chosen study location was taken from NASA's renewable energy resource website (Surface Meteorology and Solar Energy). **Fig.10** depicts the monthly average wind speed, which is 4 m/s. Based on a local load assessment, the normal electrical load of one family in Vellore city was determined in this study. Lighting, television, fans, and refrigeration are the most energy-intensive activities. The supplied load power in this case was 8.7kW (peak value), and the annual average energy usage was 11.13kWh/day. The load profile of one family in the study area is depicted in **Fig.11.**

In this project, grey wolf optimizer (GWO) technique is applied to minimize the COE (Cost of energy) and LPSP (Loss of power supply probability) to find the optimal sizing of stand-alone hybrid system (PV/DG/Battery/WT). The GWO algorithm is modelled after the natural leadership structure and hunting mechanism of grey wolves. The simulation results show that GWO is able to optimally size the system easily with fast convergence and lower system capital cost compared to other meta-heuristic algorithms i.e. (PSO, GA, etc.).

Literature Survey

S.No.	Journal Paper	Authors	Description	Outcome	Year
1.	[9]	Jamiu O. Oladigbolu, Makbul a. M. Ramli, Yusuf a. Al-turki	Since grid electrification is not cost-effective option at such remote rural areas. Authors tried to build an economical RES system as well as environmental less pollutant alternative by optimal solution that has less emissions. They used HOMER software for different design options.	Hydro-Diesel-PV-wind-battery provided NPC $1.01M and COE $0.106/kWh. hydro-wind-diesel-battery presented best economical design while selected hydro-Diesel-PV-wind-battery design presented more efficient and performance parameters as well as emissions concerns. On grounds reality the initial investments and other costs proposed by HOMER were not affordable	**2020**

				to the author's case study.	
2.	[1]	Abba Lawan Bukara, Chee Wei Tana, Kwan Yiew Lau	This paper used a latest nature - inspired metaheuristic optimization algorithm named Grasshopper Optimization Algorithm in microgrid system sizing design problem.	The proposed algorithm results confirm that GOA is able to optimally size the system as compared to its counterparts, CS and PSO. In which, a decrement of 14% and 19.3% is achieved in the system capital cost, respectively.	**2019**
3.	[7]	Habib ur Rahman Habib, Shaorong Wang, Mahmoud F. Elmorshedy, M. R. Elkadeem	To serve the customers with high power quality and reliability, design optimization methodology and a possible power management strategy (PMS) for wind diesel-battery-	Firstly, design the most feasible and cost-effective solution with least life-cycle cost, keeping in view the impact of carbon emissions. Secondly a suitable PMS that targets to maintain load	**2019**

			converter hybrid renewable energy system (HRES) is proposed in this paper.	balance and extract maximum wind power while keeping the battery SOC within the safe range	
4.	[14]	Nur Dalilah Nordin, Hasimah Abdul Rahman	Loss of power supply probability analysis is set as a benchmark to determine all possible PV array and battery capacity. The case study, with reference to Malaysia	A new method for optimal sizing of standalone system by using amp-hour analysis. Components sizing are optimally selected based on the lowest LCOE, which are able to fulfil LPSP system requirement. This method is not only flexible to be used at any sites, but it also allows designers to find optimum	**2016**

				design based on a preselected	
5.	[13]	Y. V. Pavan Kumar, Ravikumar BHIMASINGU	To promote use of non-conventional sources of energy usage, authors try to build a feasible and optimal solution using PV-wind turbines. Sensitivity analysis is performed to deal with uncertainties such as the increase in electricity consumption and grid tariff, environmental changes by reducing CO2 emissions	The most economic system configuration is achieved for the combination of 600 kW utility grid contribution, 180 kW PV contribution, and 3 units WT ,33 batteries (1 string) and a 160-kW converter. The levelized cost of energy achieved as 0.092 $/kWh which is less than the grid only connected system. priority load variation is more influential to TNPC than deferred load. Any critical	**2015**

				and large consumers of urban buildings can be integrated to a green and hybrid power system designs.	
6.	[15]	Nur Dalilah Nordin, Hasimah Abdul Rahman	Design a stand-alone photovoltaic system, the system to fulfil load demand, close to its point of utilization that include sizing of PV modules, battery storages, charge controller and inverter.	Economic assessment was employed by life cycle cost and levelized cost of energy analysis. LCC for the proposed system in 25 years is RM 34,232. The LCOE is RM 1.76/kWh. The method can be improved using hourly analysis.	**2015**

Chapter 2

Modelling of the Hybrid system

The hybrid system consists of photovoltaic modules (PV), wind turbine, battery storage system and diesel generator (DG) as shown in **Fig.1**. The modelling of the system components is required prior to the proper sizing of the HRES. Therefore, a detailed modelling of the system components is follows.

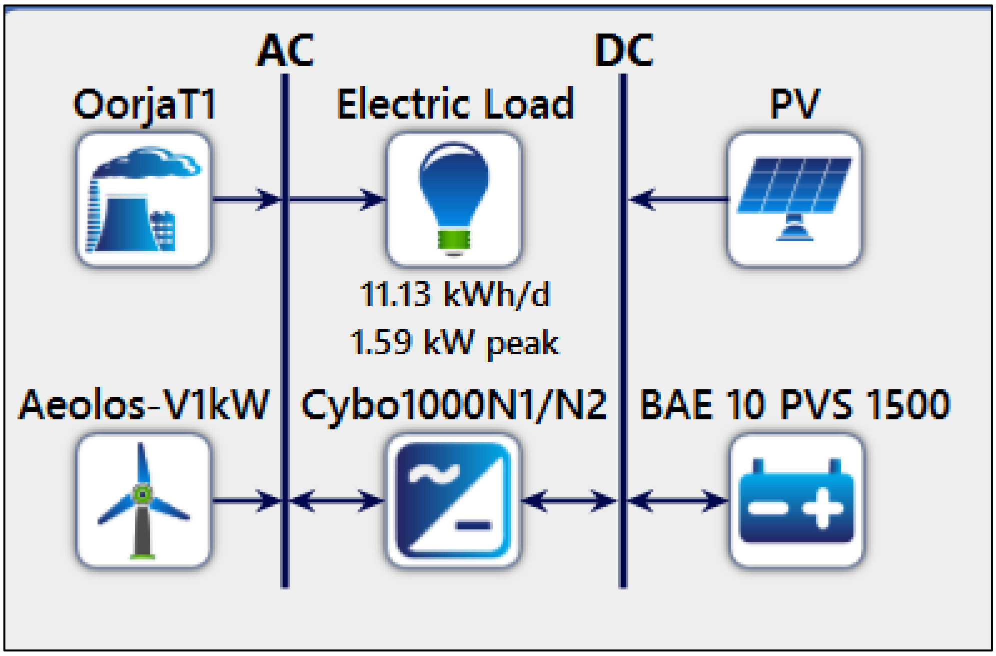


Fig.1. Architecture of microgrid system

2.1. Photovoltaic system

The power output of PV (P_{pv_out}) is calculated based on the ambient temperature and solar irradiance, as shown in the equation [1] **Eq.1.**

$$P_{pv}(\mathrm{t}) = P_{pv\_rated} \times \frac{G_t(\mathrm{t})}{1000} \times \left[1 + \alpha_t \left(\left(T_{amb} + (0.0256 \times G_t)\right) - T_{C_{STC}}\right)\right] \quad \ldots (1)$$

Where,

Ppv is the Output power (W) of the PV module

Gt is the solar irradiance (W/m^2)

Ppv_rated is the rated power (W) of the PV module at standard test condition (STC)

α_t is the temperature coefficient defined by (-3.7 *10^{-3} $\left(1/_{°C}\right)$)

Tc_stc is the cell temperature (°C) At STC

T_{amb} is the ambient temperature (°C)

2.2. Wind turbine

To calculate the wind turbine (WT) power output, the measured wind speed at anemometer height is initially converted to corresponding wind turbine hub height using the power law equation [1] **Eq.2**

$$V_2 = V_1 \times \left({}^{h}/_{h_{ref}}\right)^{\beta}$$

… (2)

Where,

V_2 and V_1 denotes the wind speed (m/s)

h is the wind turbine hub height (m)

h_{ref} is the anemometer height (m)

β is the power law exponential

The output power of wind turbine (P_{wt}) is calculated using the power curve equation [1] **Eq.3** as

$$P_{WT} = \begin{Bmatrix} 0 & V < V_{Cut\_in}, V > V_{Cut\_out} \\ V^3\left(\frac{P_r}{V_{Rated}^3 - V_{Cut\_in}^3}\right) - P_r\left(\frac{V_{Cut\_in}^3}{V_{Rated}^3 - V_{Cut\_in}^3}\right) & V_{Cut\_in} \leq V < V_{Rated} \\ P_r & V_{Rated} \leq V < V_{Cut\_out} \end{Bmatrix}$$

… (3)

Where,

V is the wind speed (m/s)

P_r is the rated power (kW)

V_{cut-in} is the cut-in speed of the WT (m/s)

V_{Rated} is the rated speed of the WT (m/s)

$V_{cut-out}$ is the cut-out speed of the WT (m/s)

2.3. Battery

Battery is operated during periods of non-availability of renewable energy source to meet the energy demand and as energy storage where excess power is used for charging the battery. In this case, the capacity of the battery is calculated, taking into account the target autonomy day (AD) and load demand. Autonomy days refers to number of days a battery bank would be able to meet the energy demand of the load. The Battery capacity (B_{cap}) is calculated as show in the equation [1] **Eq. 4**.

$$B_{cap} = \frac{AD.P_l}{\eta_{inv}.\eta_B DOD}$$

… (4)

Where,

η_{inv} is the efficiency of the inverter

η_B is the efficiency of the battery

DOD denotes the depth of discharge of the battery

P_l denotes the total load demand

2.4. Diesel generator

The fuel usage rate ($F_{(t)}$) of a diesel generator is expressed **(5)** as [1]

$$F_{(t)} = 0.246P_{DG}(t) + 0.08415P_r$$

… (5)

Where,

P_{DG} is the power generated by diesel generator (kW)

$F_{(t)}$ is the fuel consumption (L/hour)

$P_{(r)}$ is the rated power of the diesel generator (kW)

The cost of the fuel usage is expressed **(6)** as [1]

$$C_F = P_{fuel} F_t \quad \dots (6)$$

Where P_{fuel} is the fuel cost (US$/l)

Chapter 3

Grey Wolf Optimizer (GWO)

Mirjalili and Lewis proposed the Grey Wolf Optimizer (GWO) algorithm in 2014. This algorithm was inspired primarily by the social leadership and hunting strategy of grey wolves. The grey wolf (Canis lupus) is a member of the Canidae family. Grey wolves are apex predators, which means they are at the top of the food chain.[11] They have a very tight social dominating hierarchy, which is of great relevance as shown in [2] **Fig.2**.

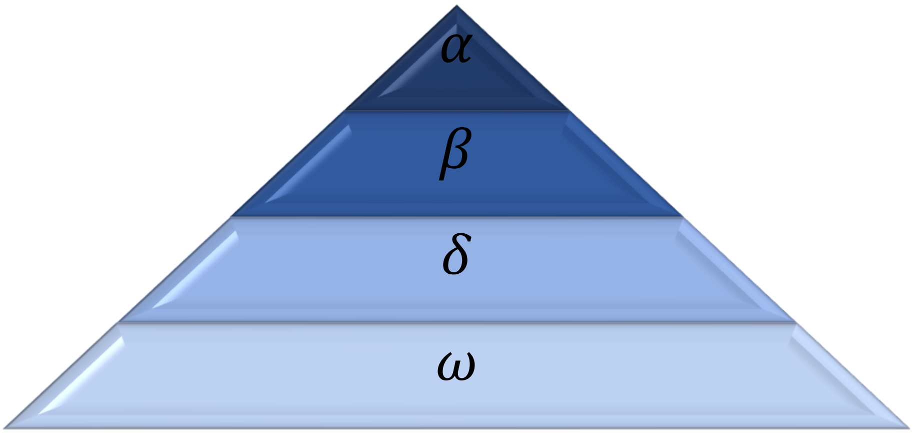


Fig.2. Hierarchy of grey wolves (dominance decreases from top down)

Alphas are male and female leaders. They are responsible for decision making about hunting, sleeping, location, walking time and so on. The pack is dictated to by the alpha's decisions.

The grey wolf hierarchy's second level is beta. The betas are subordinate wolves who assist the alpha in pack decision-making and other duties. The beta reinforces the alpha's directives throughout the pack and provides feedback to the alpha.

The grey wolf with the lowest ranking is omega. The omega serves as a scapegoat. Omega wolves must always subordinate to all other dominant wolves. Although it may appear that the omega is not an important member of the pack, it has been found that when the omega is lost, the entire pack suffers from internal fighting and issues. The omega in some situations is also the pack's babysitters.[2]

A wolf is termed delta if he or she is not an alpha, beta, or omega. Delta wolves must subject to alpha and beta wolves, but they rule the omega. This group includes scouts, sentinels, elders, hunters, and caretakers.

To mathematical model the social hierarchy of wolves when designing Grey wolf optimizer (GWO), alpha (α) Wolf is thought to be the fittest solution.[11] Consequently, the second and third best solutions are considered as beta (β) And delta (￼) Wolves, respectively. The remaining possible solutions are presumed to be omega (￼) Wolves. The hunting (Optimization) in the GWO algorithm is directed by α, β, and δ. The ω wolves trail these three wolves in their pursuit of the global optimum.

The encircling behaviour of the grey wolves during the hunting process is mathematically modelled as shown in [11] **Eq. (7-8)**.

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_p}(t) - \vec{X}(t)\right|$$

… (7)

$$\overrightarrow{X(t+1)} = \overrightarrow{X_p}(t) - \vec{A}.\vec{D}$$

… (8)

Where,

$\vec{X}$ is the position vector of the grey wolf

$\overrightarrow{X_p}$ is the position vector of the prey

t is the current iteration

$\vec{A}$, $\vec{C}$ are the coefficients vectors obtained by [11] **Eq. (7a-8a)**

$$\vec{A} = 2\vec{a}.\overrightarrow{r_1} - \vec{a}$$

… (7a)

$$\vec{C} = 2\overrightarrow{r_2}$$

… (8a)

Where,

r1 and r2 are the random vectors in [0,1]

$\vec{a}$ linearly decreased from 2 to 0 over the course iterations

Grey wolves can recognise their prey's location and encircle it with the help of the alpha. However, we have no idea where the optimal (prey) is in an abstract search space. In order to mathematically replicate grey wolf hunting behaviour, we assume that the alpha, beta, and delta have superior knowledge of the probable location of prey. Therefore, the first three best solutions produced thus far obligate the other search agents such as the omegas to update their locations in accordance with the position of the best search agents. The following update formulas [2,11] **Eq. (9-15)** can be used to numerically model this process:

$$\overrightarrow{D_\alpha} = \left|\overrightarrow{C_1}.\overrightarrow{X_\alpha} - \vec{X}\right|$$

… (9)

$$\overrightarrow{D_\beta} = \left|\overrightarrow{C_2}.\overrightarrow{X_\beta} - \vec{X}\right|$$

… (10)

$$\overrightarrow{D_\delta} = \left|\overrightarrow{C_3}.\overrightarrow{X_\delta} - \vec{X}\right|$$

… (11)

$$\vec{X}_1 = \overrightarrow{X_\alpha} - \overrightarrow{A_1}.\overrightarrow{D_\alpha}$$

… (12)

$$\vec{X}_2 = \overrightarrow{X_\beta} - \overrightarrow{A_2}.\overrightarrow{D_\beta}$$

… (13)

$$\vec{X}_3 = \overrightarrow{X_\delta} - \overrightarrow{A_3}.\overrightarrow{D_\delta}$$

… (14)

$$\vec{X}(t+1) = \frac{\overrightarrow{X_1} + \overrightarrow{X_2} + \overrightarrow{X_3}}{3}$$

… (15)

When the prey stops moving, the hunting behaviours are completed by attacking it. This can be modelled mathematically by reducing the value of the $\vec{a}$ from 2 to 0 which decreases the value $\vec{A}$. When the values of $\vec{A}$ falls in the interval [-1, 1], grey wolves attack the prey. If $|\vec{A}| > 1$ candidate solutions will diverge from the prey and converge toward the prey when $|\vec{A}| < 1$. $\vec{C}$ is yet another GWO component that encourages exploration. The $\vec{C}$ vector generates random values in the range [0, 2], with random weights for prey provided to stochastically emphasize (C > 1) or deemphasize (C < 1) the effect of prey in defining the distance.[2] To emphasise exploration not just during first iterations but also during final iterations, the C parameter was necessary to supply random values at all times. This component is quite useful for dealing with local optima stagnation, particularly in the final iterations. The pseudo code of the grey wolf optimizer is illustrated in [11] **Fig. 3**.

Begin of algorithm
Initialize the grey wolf population X_i = 1,2,....n
Initialize the parameters A, a and C
Calculate the fitness of each search agent
X_α the best search agent
X_β the second best search agent
X_δ the third best search agent
While t < Max_number of iterations
for each search agent
Update the position of the current search agent
End
Update the parameters a, A and C
Calculate the fitness of search agent
Update the fitness of search agent
Update the X_α, X_β and X_δ
t = t+1
End
return X_α

Fig.3. Pseudo code of the GWO

Chapter 4

Objective function

Various evaluation criteria have been published to evaluate the optimal design of HRES. The majority of these indices were based on specific economic factors such as NPC (also known as life cycle cost), levelized energy cost, system total cost, system annualised cost, average generating cost, and so on. [7] The major goal of the optimization problem in this project is to minimise total LPSP and COE such that a stable power source might be provided at a low cost.

4.1 Levelized cost of Energy (LCOE)

The average cost per kWh of useable electrical energy produced by the system is known as the levelized cost of energy (COE). To calculate the COE, the annualized cost of producing electricity is divided by the total electric load served, using the following equation [12] **Eq.16**:

$$COE = \frac{C_{t,ann}}{E_{t,ann}}$$

… (16)

Where,

$C_{t,\,ann}$ is the total system annualized cost ($/yrs.)

$E_{t,\,ann}$ is the total electrical load served (kWh/yrs.)

The annualised value of the total net present cost is annualised cost of the system. And it is calculated by the formula [12] **Eq.17**

$$C_{t,ann} = CRF \times NPC$$

… (17)

Where,

NPC is the net present cost ($) of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime.[12] Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue.

$$NPC = C_{pv} + C_{battery} + C_{inv} + C_{WT} + C_{DG} + C_{batrep} + C_{DGrep} + C_{O\&M} - C_{salvage}$$

… (18)

CRF is the capital recovery factor (CRF) is a ratio that is used to assess an annuity's present value (a series of equal annual cash flows). The capital recovery factor is calculated as follows [12] **Eq.19**

$$CRF = \frac{i(i+1)^N}{i(i+1)^N + 1}$$

… (19)

Where,

i is the real discount rate used to convert between one-time costs and annualized costs. It calculates the annual real discount rate (also called the real interest rate or interest rate) from the "Nominal discount rate" and "Expected inflation rate".[12] It is calculated as **Eq.20**

$$i = \frac{i - f}{1 + f}$$

… (20)

i is nominal discount rate (the rate at which money is borrowed)

f is the expected inflation rate

N denotes the project lifetime is the period of time during which the system's expenditures are incurred.

Inflation is factored out of the economic study by defining the real discount rate in this way.[12] As a result, all costs become actual costs, which are measured in constant dollars. The assumption is that all costs will experience the same rate of inflation.

4.2. Loss of Power Supply Probability

The percentage times of a loss of power supply, which means the combined (PV and energy storage or whatever the energy sources the microgrid design supposed to fulfil the demand) system is unable to serve the load on demand, is known as the LPSP. It is an excellent indicator of the system's performance for an expected or known load distribution and other system factors.[3]

$$LPSP = \frac{\sum_{t=1}^{8640} LPS(t)}{\sum_{t=1}^{8640} LD(t)}$$

… (21)

Where,

LPS is the loss power supply

LD is the load demand

The value of LPSP ranges between (0-1). When the LPSP value is zero, the energy demand is completely met. Similarly, LPSP equal to unity indicates that the energy demand has not been met.[3]

4.3. Design Variables

The design variables considered for the optimal design of the system are the number of PV panels, number of wind turbines, number of DG and autonomy days (AD). The limits of the variables are shown in [1] **Eq.22**

$$Design\,Variables = \begin{cases} 0 \leq N^{pv} \leq 45 \\ 0 \leq N^{wt} \leq 10 \\ 0 \leq N^{DG} \leq 4 \\ 0 \leq N^{AD} \leq 3 \end{cases}$$

… (22)

Chapter 5

Load Following strategy

A reliable energy management system (EMS) is one of the most important factors to consider while developing a microgrid. The EMS's goal is to coordinate power flow among the numerous components that comprise the microgrid. EMS also helps to reduce battery degradation, increase the efficiency of the renewable energy system (PV and WT), and reduce fuel usage. It also improves system efficiency, resulting in substantial cost and energy savings. The charging and discharging of battery are determined by the power generated by the renewable sources and load demand at hour t. [1] The DGs are linked to the AC bus system and immediately provide the load requirement without the use of any conversion devices. This system also employs the dump load, which has the role of discharging excess power once the renewable energy power exceeds the charge and the battery banks are fully charged. The power management strategy of microgrid is shown in [1] **Fig.4**. The modes of operation of EMS controller are as follows:

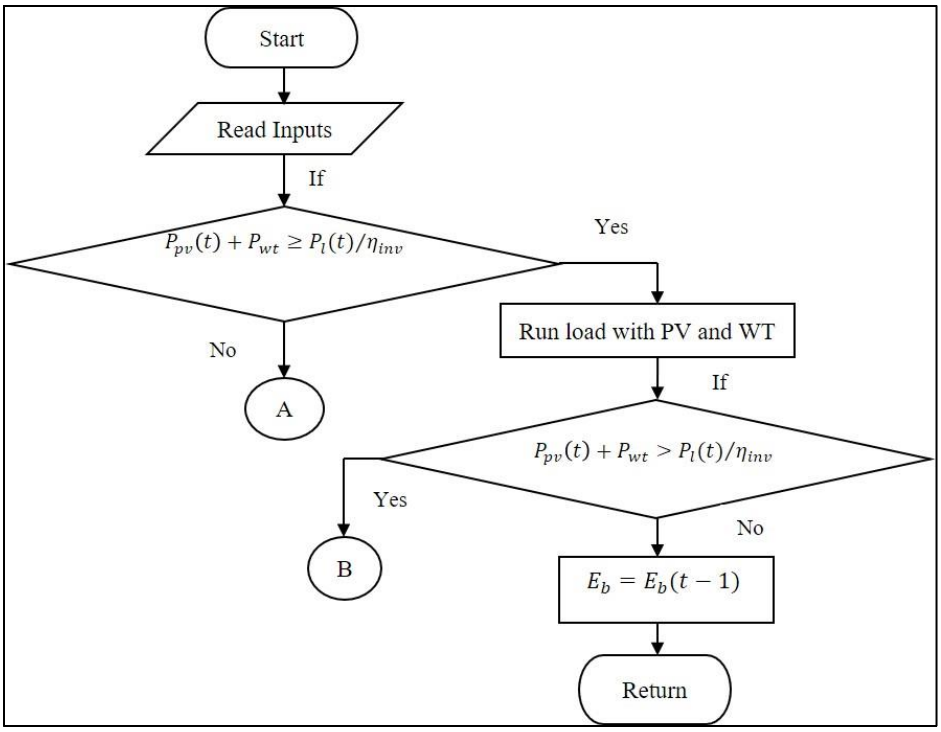


Fig.4. Power management Strategy

Mode-1: If power generated by the renewable energy system exceed the load demand the excess power is used to charge the battery banks, the charging operation process is show in **Fig.5**.

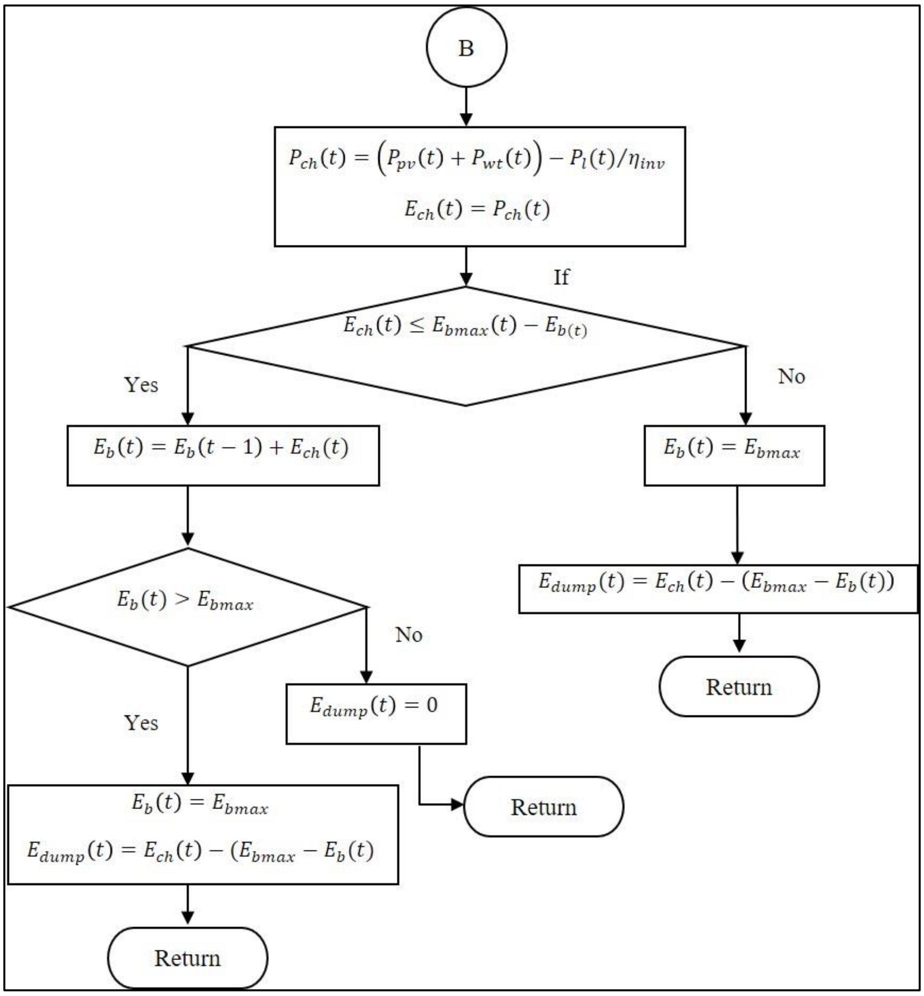


Fig.5. Operation during battery charging

Mode-2: If the value of energy generated by the RE system exceeds the load demand and battery is fully charged, then excess energy will be squandered in order to dump load.

Mode-3: If the value of power generated by RE system is insufficient to fulfil energy demand and battery banks have sufficient energy to handle the remaining power, then the battery banks begin to discharge. When the battery banks fail to deliver the remaining power, the diesel generator is activated. The discharge process is shown in the **Fig.6**.

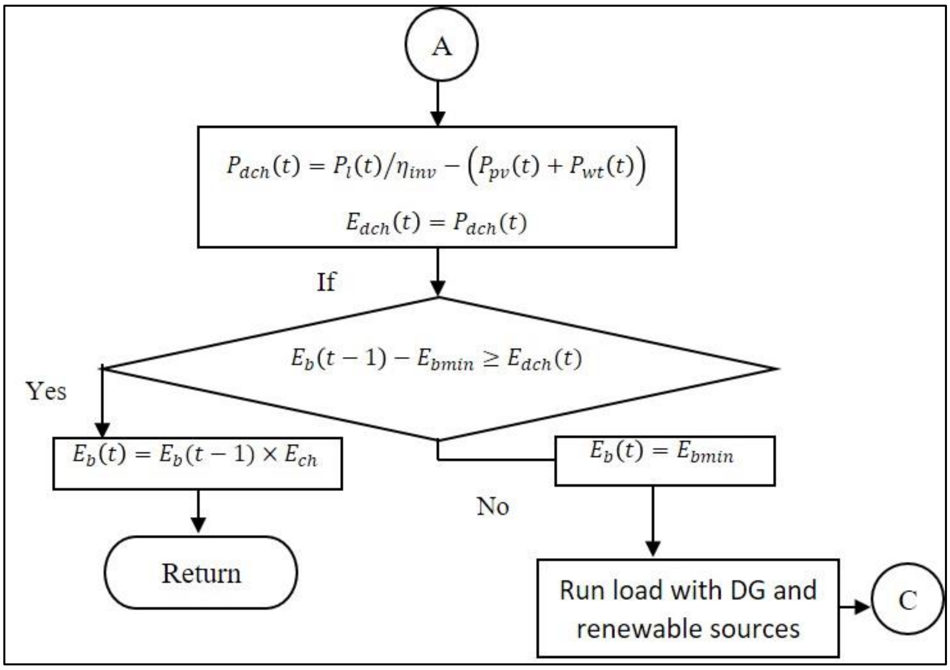


Fig.6. Operation during battery discharging

Mode-4: Energy generated by the RE system is insufficient to fulfil load demand and battery banks have insufficient energy to support the demand, then DG is activated and supply the load as well as charge the battery. When the RE system begins to generate power, the DG stops charging the battery banks. The operation of diesel generator is shown in **Fig.7**.

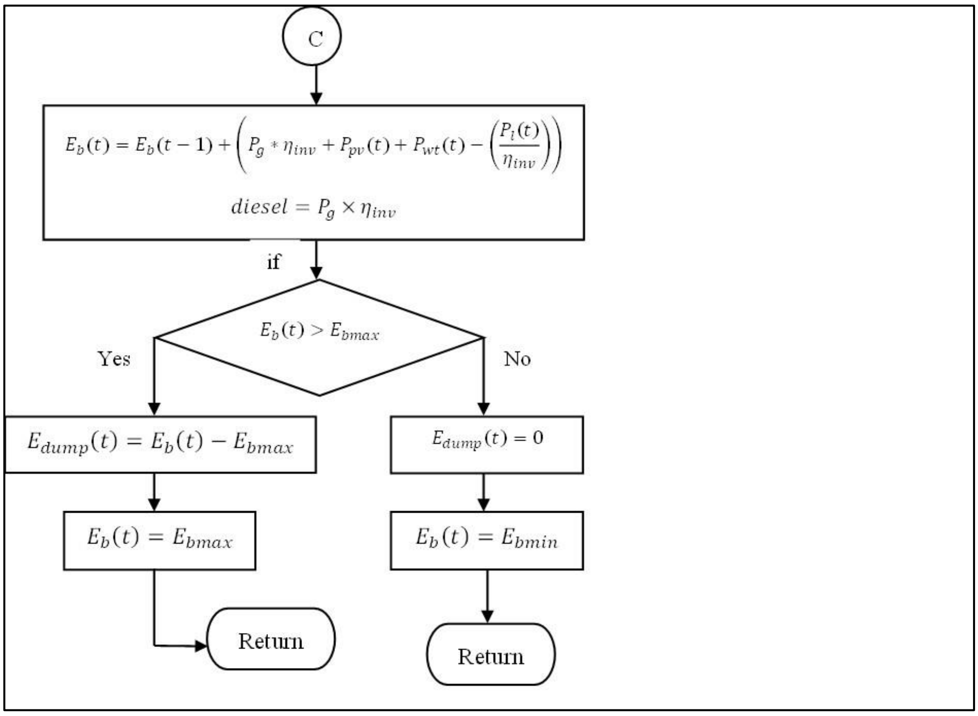


Fig.7. Operation of diesel generator

Chapter 6

Simulation Results

The developed GWO code technique is implemented in the MATLAB and applied to the design of an autonomous hybrid microgrid PV-WT-Battery-DG system problem, which is intended to meet the energy demand of residential housing in an off-grid situation. The simulation reaches LPSP value close to zero percent, implying that the energy demand is completely supplied.[6] The electric demand for various solar insolation, ambient temperature, and wind speed is provided in **Fig.8-11**. The specifications and price of different design component is given in the **Table 1**.

6.1. Technical and Economic specifications of system components

Table 1. Specifications of system components

	Description	Parameters	Values	Units
A	Battery	Lifespan	2	Years
		Efficiency	85%	%
		Rated capacity	40	kWh
		Initial cost	280	$/kW
B	WT	Lifespan	24	Years
		Cut-in speed	2.5	m/s
		Cut-out speed	25	m/s
		Efficiency	95	%
		Wind turbine regulator cost	1000	$
		Rated power	1	kW
		Price	3	$/W
C	PV	Lifespan	24	Years
		Efficiency	95	%
		Rated Power	275	W

		PV regulator cost	1500	$
		Initial cost	2.15	$/W
D	Diesel generator	Rated power	4	kW
		Initial cost	1000	$/kW
		Life time	24000	Hours
E	Inverter	Lifespan	24	years
		Efficiency	92	%
		Initial cost	2500	$
F	Economic parameters	Real interest	13%	%
		Fuel inflation rate	5	%
		Running cost + O&M	20	%
		Project lifetime	24	Years
		Discount rate	8	%
G	GWO	Wolf pack size	5	
		Iterations	100	

6.2. Climate consideration and load profile for system design

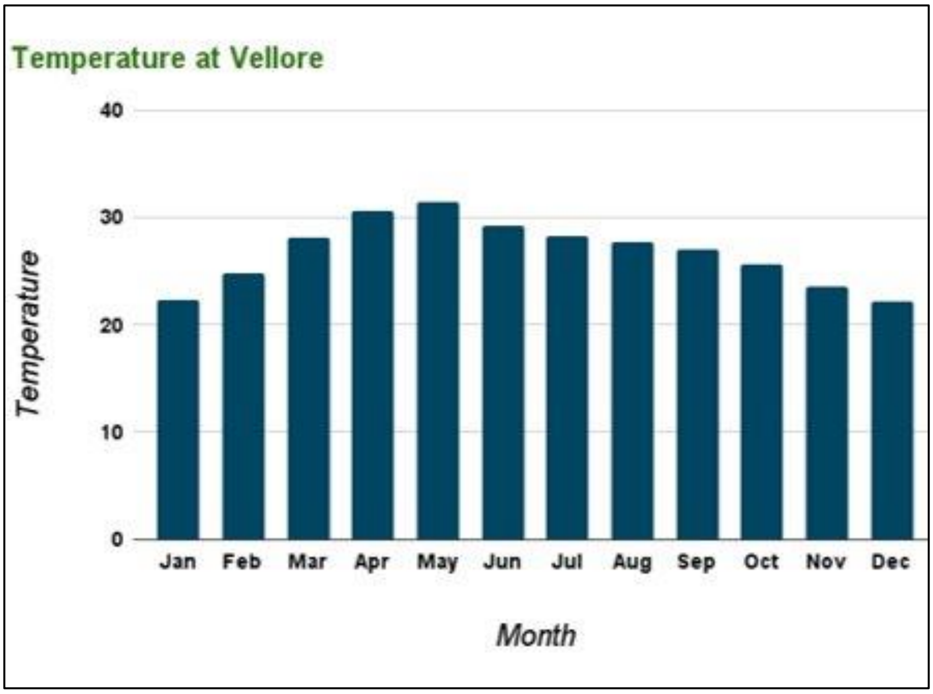


Fig.8. Temperature at Vellore

Figure shows the monthly average temperature at Vellore.

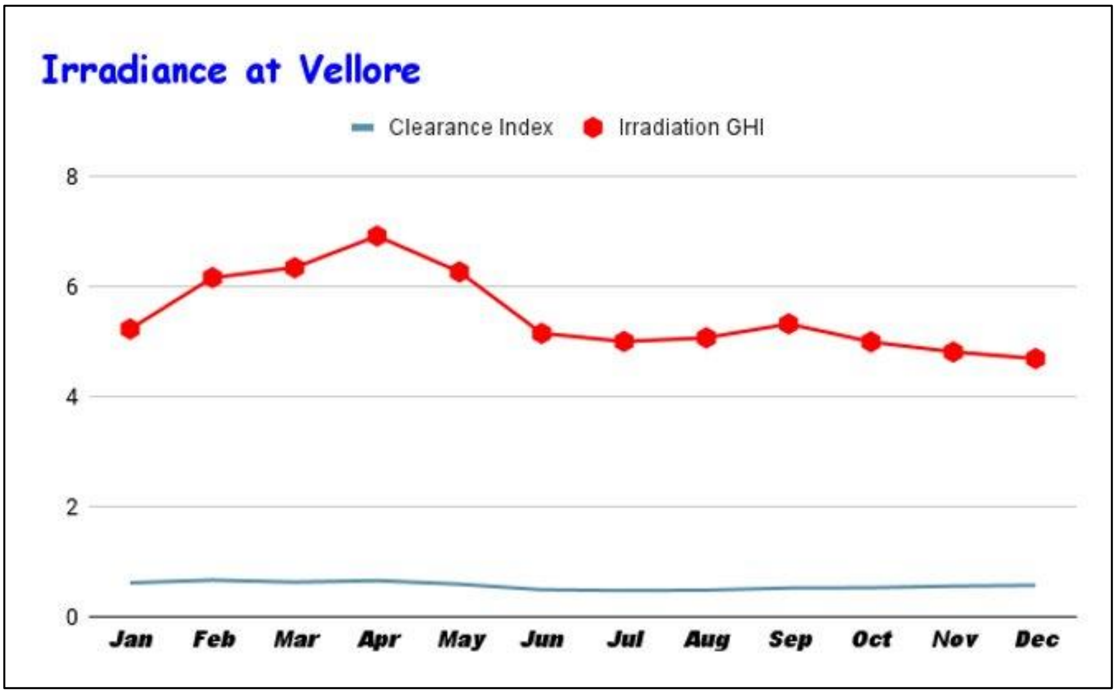


Fig.9. Irradiance at Vellore

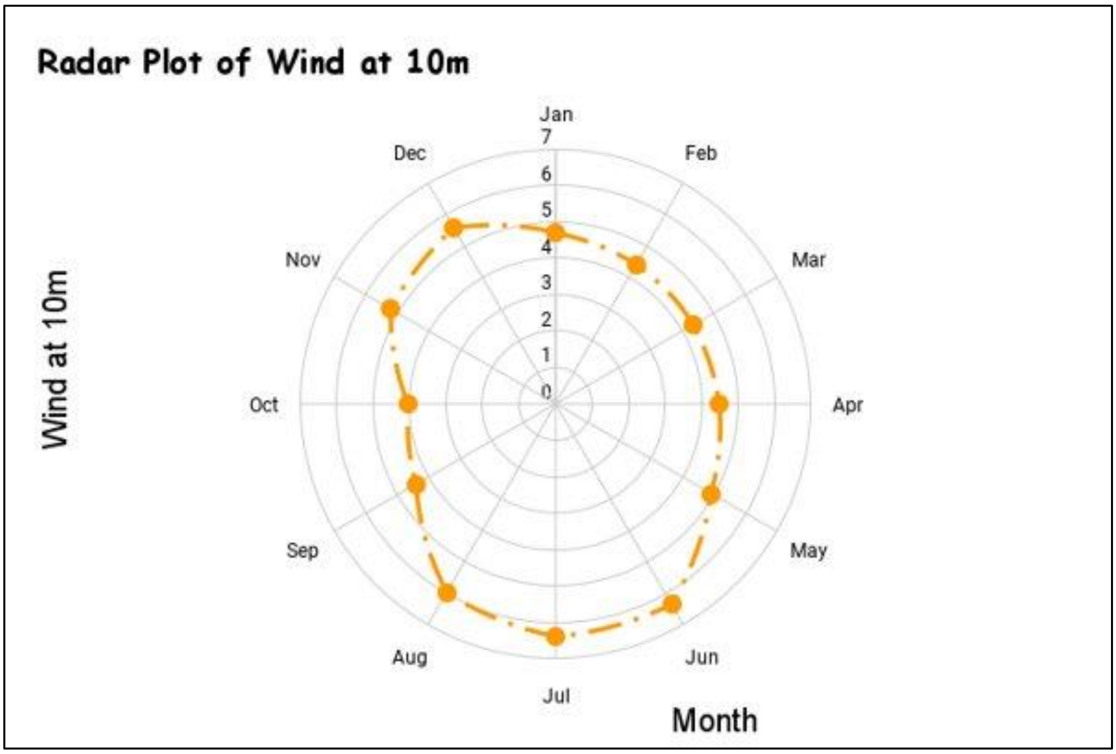


Fig.10. Wind Speed (m/s)

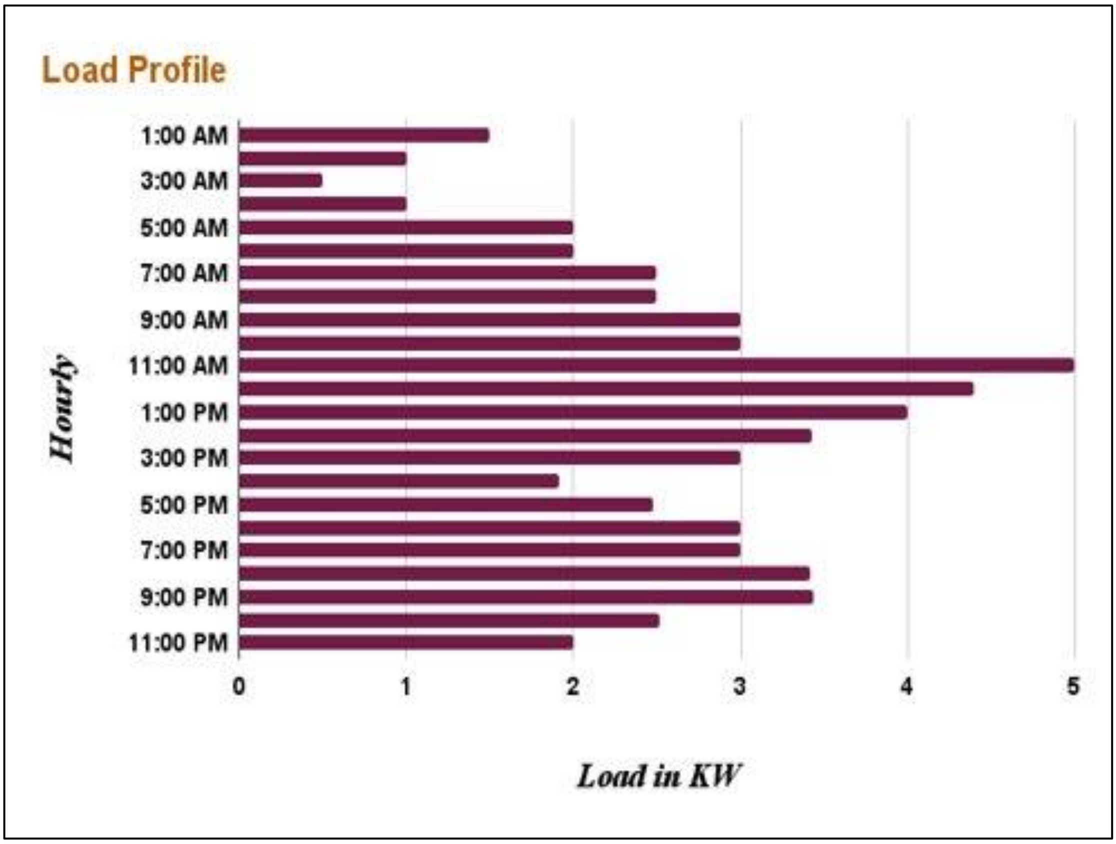


Fig.11. Residential load profile (kW)

6.3. Grey Wolf Optimizer (GWO) Vs Other Meta-Heuristic Algorithms

To ensure the reliability and validity of the proposed GWO in predicting the optimal size of the autonomous hybrid microgrid system, three other nature-based metaheuristic algorithms, PSO, CS and GOA, with reference to base journal [14,1] are used with the same components and expenses as in the journal [1] to provide the best solution. The collected results are compared to the proposed GWO's outcomes show in the **Table 2**.

Table 2. Optimal sizing results obtained

Optimal design parameters	GWO	GOA	CS	PSO
LPSP	0	0	0	0
AD	3	3	3	2
Number of PV panel	21	26	29	30
Number of WT	5	4	6	7
Diesel generator capacity (kW)	4	4	4	4
Battery Capacity (kW)	40	40	40	40

COE ($/kWh)	0.31094	0.3656	0.3662	0.3674
NPC ($)	39273.5	47572.5	55346.25	58937.5

6.4. MATLAB SIMULATION OUTPUT

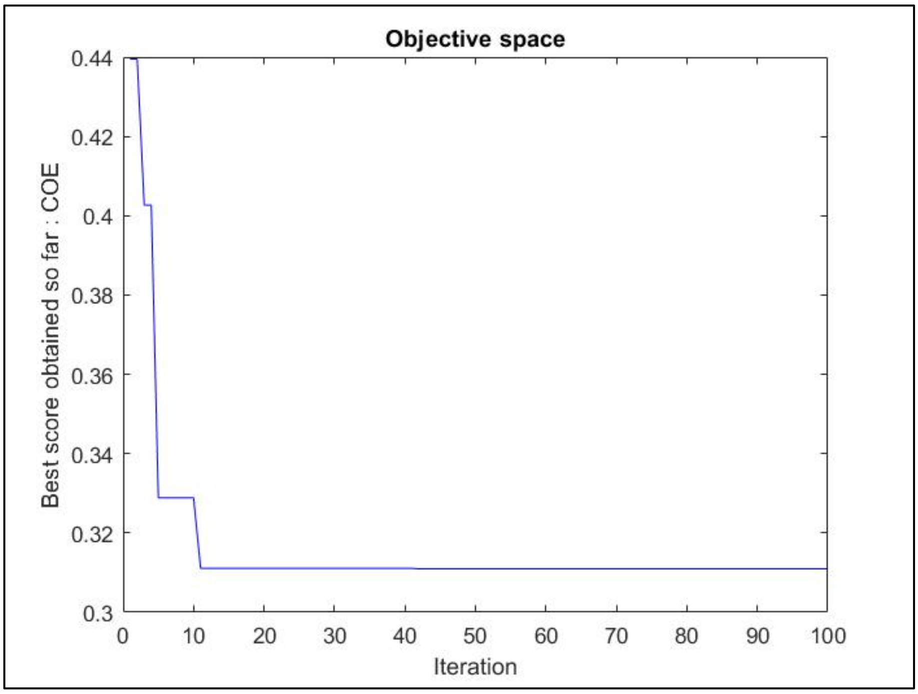


Fig.12. COE convergence graph

Fig.12 depicts the convergence characteristics of GWO for the autonomous microgrid. The convergence plot's abscissa represents the iteration estimate, while the ordinate represents the COE. The value of the COE drops during the iteration process, as seen in **Fig. 12**. This suggests that the optimization process minimises the COE by aiming for the smallest possible system size.[4] Because the wolf packs are dispersed at first, they eventually converge to the lowest value possible depending on the optimal solution direction provided by beta and delta wolves. Therefore, any decrease in the objective function is significant since it leads to additional information regarding the optimal size.

Fig.13 illustrates the convergence characteristics of LPSP. Over the iteration the value of loss of power supply probability converges to the least possible value which was approximately 0.043446 which is close to zero. Zero LPSP signifies there is no unmet load demand.

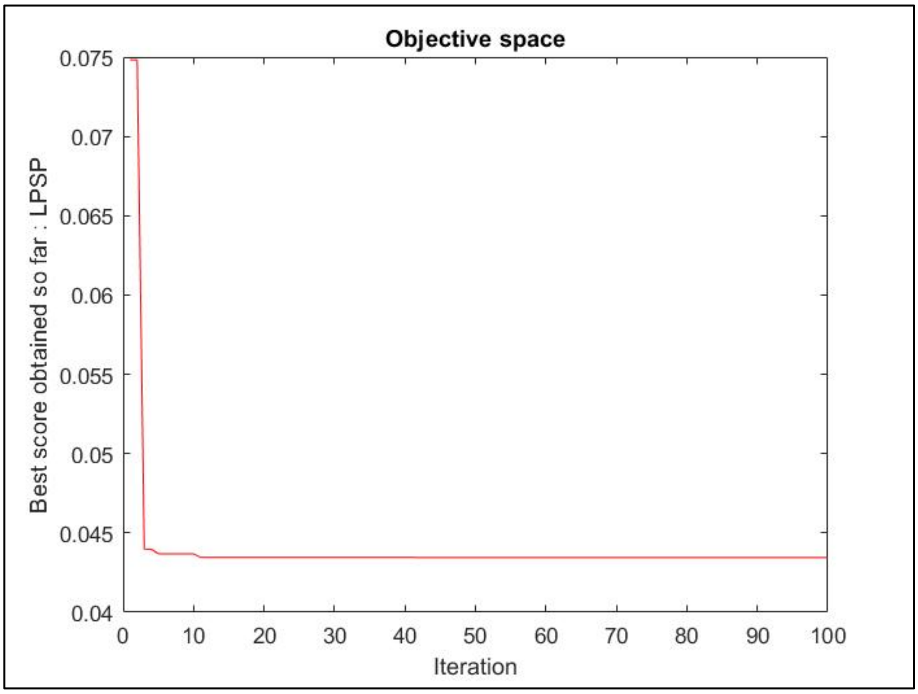


Fig.13. LPSP convergence graph

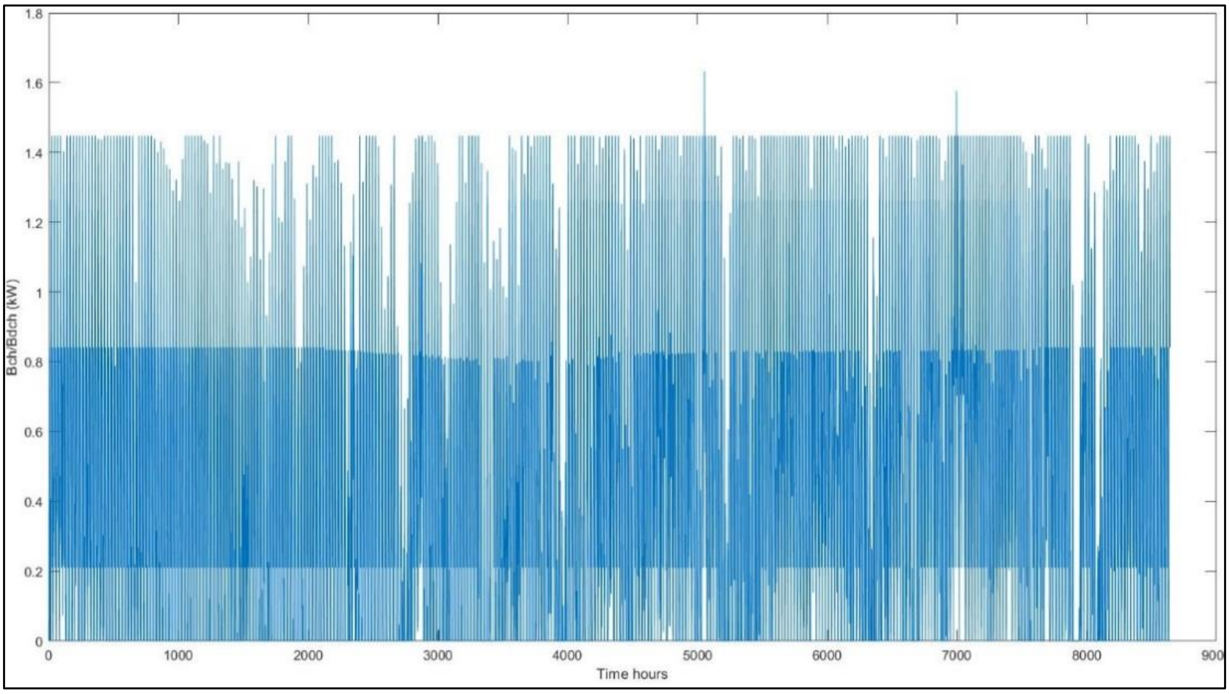


Fig.14. Battery backup power supply

As seen in **Fig. 14**, the battery is heavily used and fragile throughout the hot season, as opposed to the rainy and cold seasons. This is because to the depreciation in insolation or sun hours during rainy –winter seasons. Since production from PV is not able to meet demand, it needs to be channelled to storage unit to be used by load.[4] Else work parallel with battery. **Fig.15** depicts the percentage of energy produced by the various system components over the year.

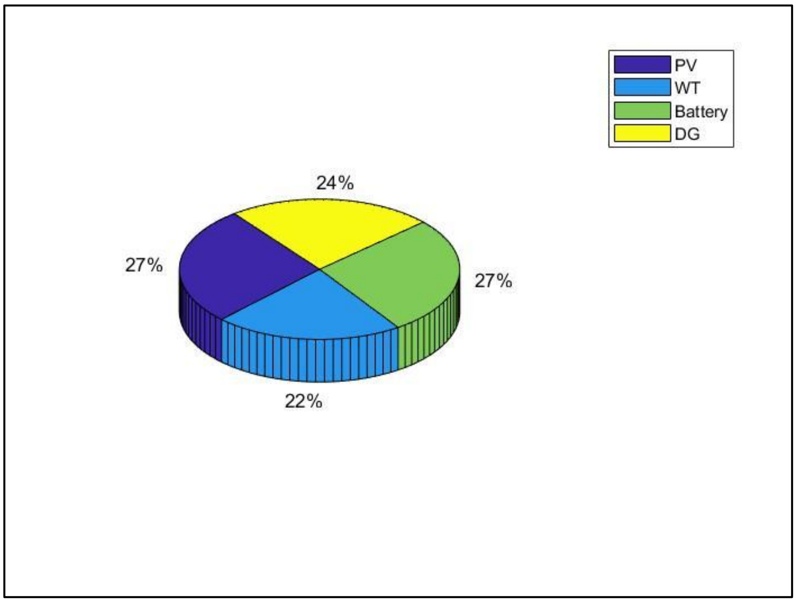


Fig.15. Annual contribution of system components

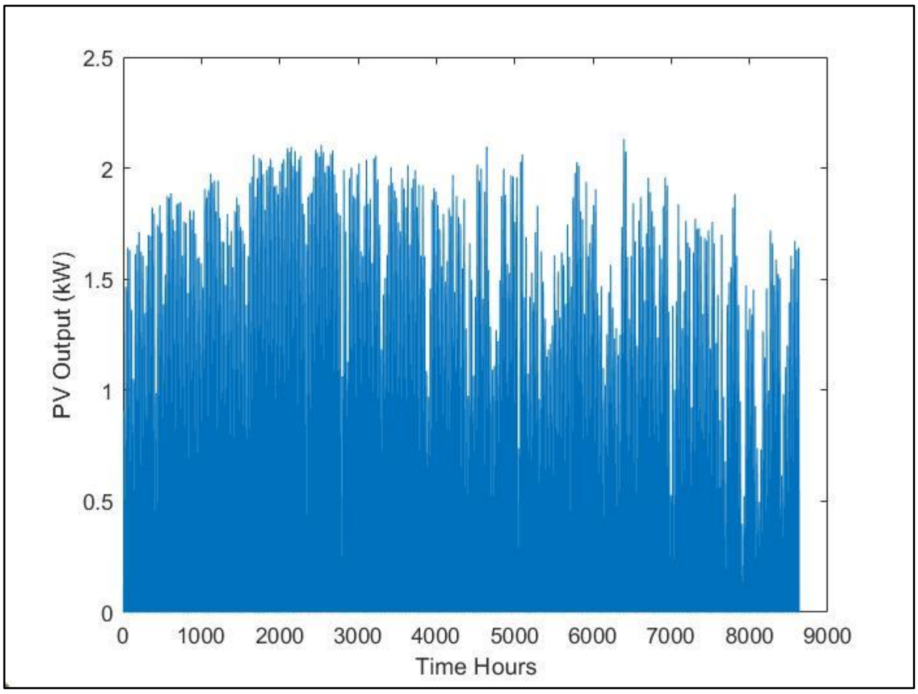


Fig.16. Hourly power generated by PV array

By **Fig.16** it is seen more populated in the left part of the year axis and scarce in the right part. As PV resource is more exploited in summer season than others.[5] According to wind speed **Fig.10**. Vellore experiences high speed during the months of Jun - August which is 3624 hrs to 5832 hrs. That explains the high energy output by wind turbines in the **Fig.17** during that part of the year.

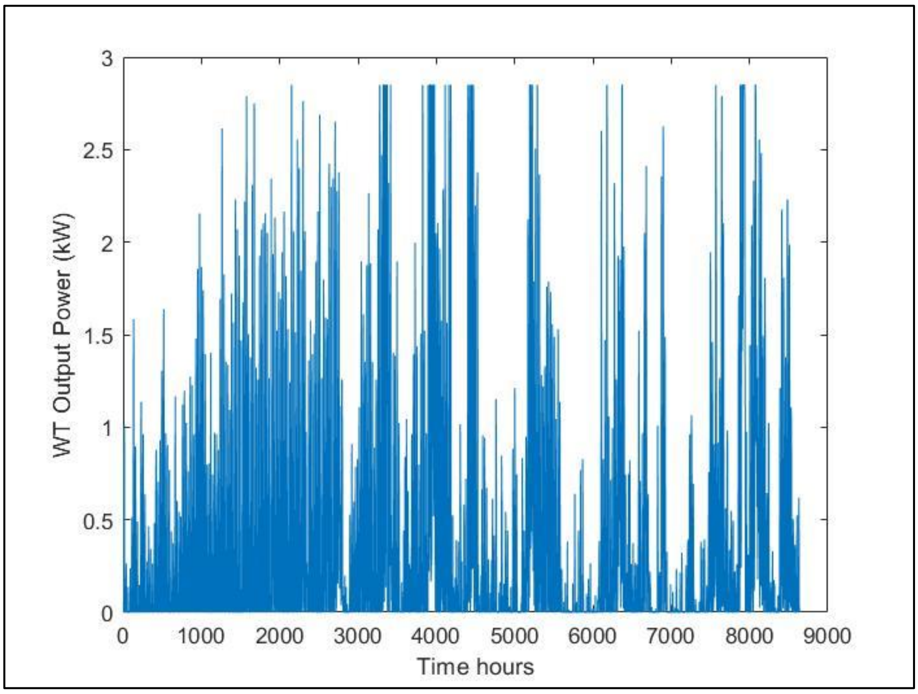


Fig.17. Power generated by wind turbine

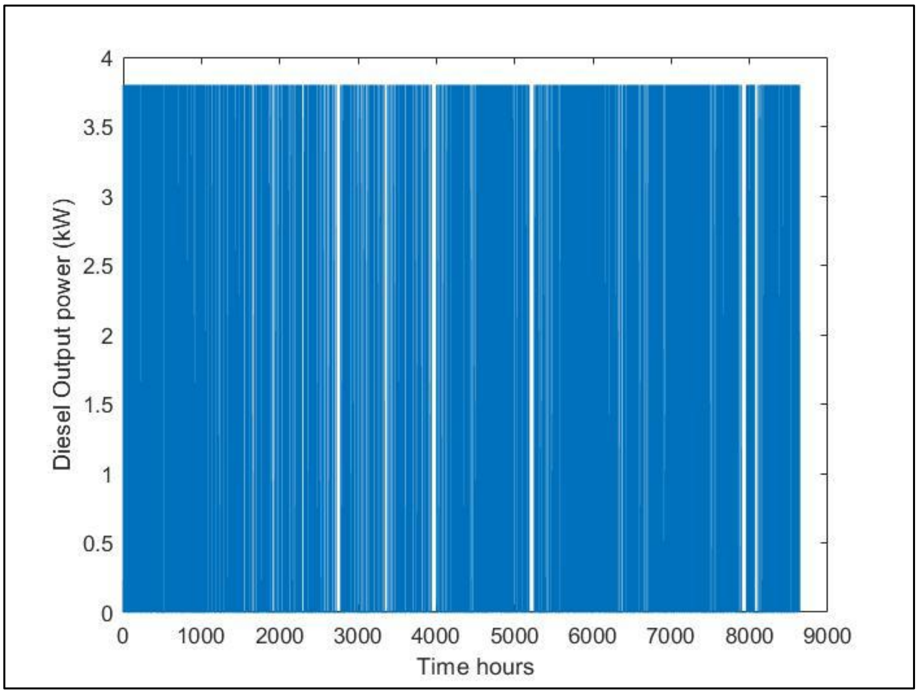


Fig.18. Diesel output power

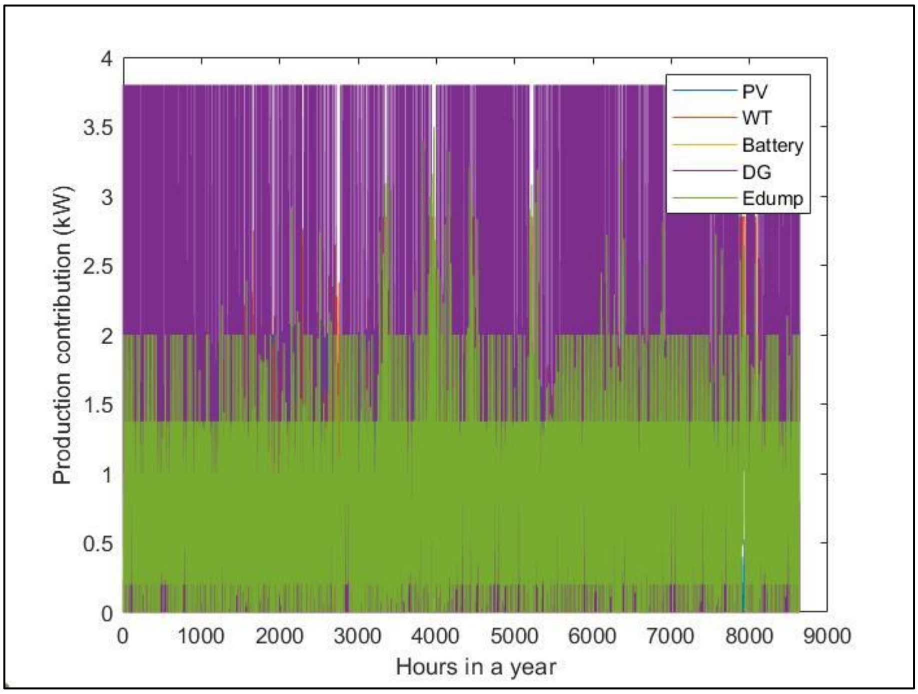


Fig.19. Electricity generation mix for a period of one year

Fig.18-19 illustrates the power output of diesel generator and electricity contribution for a period of one year.

6.5. HOMER SIMULATION RESULTS

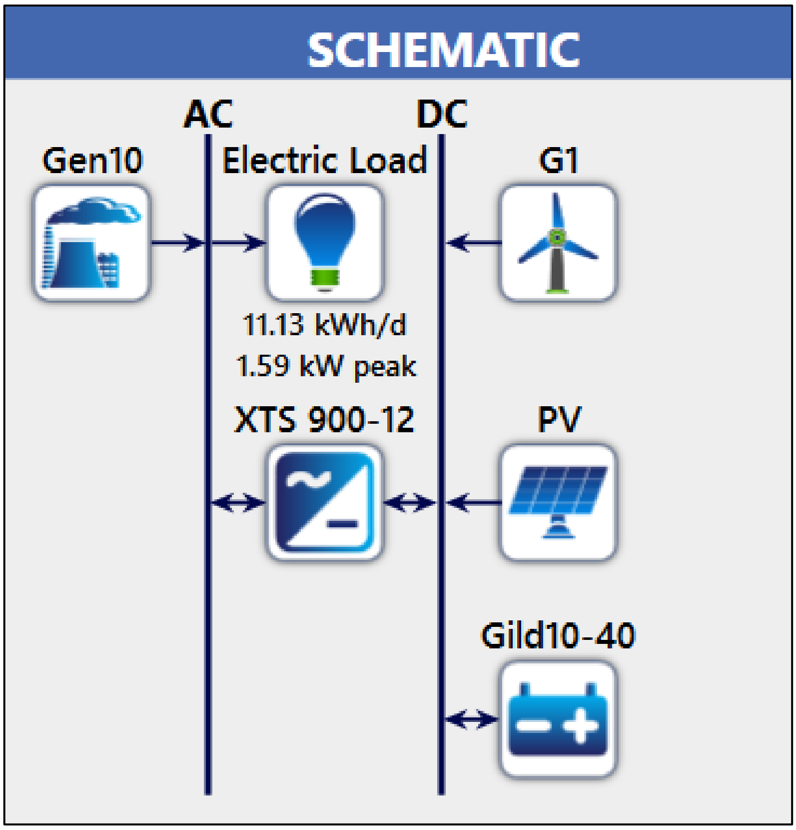


Fig.20. Schematic of microgrid system

Table.3. WT HOMER Specifications

Wind turbine parameters	Values
Manufacturer	Generic
Model	GENERIC G1
Rated power	1 kW
Peak power	1.2 kW
Cut-in speed	2.5 m/s
Cut-out speed	25 m/s
Survival wind speed	8 m/s
Hub height	25
Capital cost of wind form	3000 $/kW
Replacement cost of wind	3000 $/kW
O&M	100
Life time	24

Table.4. PV HOMER Specifications

PV parameters	Values
Manufacturer	Generic
Model	GENERIC FLAT PLATE
Rated power	1 kW
Capital cost of PV	2150 $/kW
Replacement cost of PV	2150 $/kW
O&M	10 $/y
Life time	24
Derating factor	98.6 %

Table.5. DG HOMER Specifications

DG parameters	Values
Manufacturer	Generic
Model	Generic 10
Capacity	10 kW
Initial Capital of DG	5000 $
Replacement cost of DG	5000 $

O&M	0.3 $/hr
Life time	24000 hrs
Fuel price	1 $/L

Table.6. Battery HOMER Specifications

Battery parameters	**Values**
Manufacturer	Gild Meister
Model	CELLQUBE FB 10-40
Nominal voltage	48 V
Nominal capacity	40 kWh
Nominal capacity	833 Ah
Round trip efficiency	64 %
Max. charge current	200 A
Max. Discharge current	313A
Initial Capital of Battery	280 $/kW
Replacement cost of Battery	280 $/kW
O&M	40 $/y
Life time	2 yrs.
Throughput	876000

Only the design configuration ideas were taken into account in this project. The load and other input parameters necessary throughout the simulation were kept the same for a valid comparison.[13] The **Table 7** shows the details of the various energy systems studied for the comparative analysis.

Table.7. Comparison of the technical and economic characteristics of the stand-alone hybrid energy systems

Systems	**DG-BT**	**PV-WT-DG-BT**	**PV-BT-DG**	**PV-WT-BT**	**PV-BT**
NPC	49638	22057	17978	17361	13233
COE	0.710	0.316	0.257	0.254	0.194
Operating Cost ($/y)	1879	190.36	118.31	309.02	211.59
Initial capital ($)	17319	18783	15944	12047	9594

Renewable fraction (%)	0	98.7	97.1	100	100

The Optimization Results in **Fig.21** lists all the feasible simulations for the selected sensitivity case. The results are categorized and filtered by system type. The numbers under the Architecture section indicate the presence of each type of component under consideration. Here the icons indicate the presence of, from left to right: PV, wind turbines, diesel generator, batteries and the converter. To the right are several columns that indicate a few summary values drawn from the simulation results of the least-cost system, such as the initial capital cost, operating cost, and total net present cost.

Architecture						Cost				System		
PV (kW)	G1	Gen10 (kW)	Gild10-40	XTS 900-12 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours
3.27			1	0.911	CC	$13,233	$0.194	$211.59	$9,594	100	0	
3.01	1		1	0.922	CC	$17,361	$0.254	$309.02	$12,047	100	0	
3.31		10.0	1	1.42	LF	$17,978	$0.257	$118.31	$15,944	97.1	56.2	47.0
3.21	1	10.0	1	1.44	LF	$22,057	$0.316	$190.36	$18,783	98.7	25.1	21.0
		10.0	1	4.82	CC	$49,638	$0.710	$1,879	$17,319	0	2,515	1,193
	1	10.0	1	4.88	CC	$52,411	$0.750	$1,857	$20,479	0	2,359	1,108
11.4		10.0		1.41	CC	$147,226	$2.11	$6,643	$32,972	0	7,256	6,072
11.4	1	10.0		1.39	CC	$150,762	$2.16	$6,676	$35,941	0	7,184	6,012
	19		21	1.15	CC	$159,949	$2.36	$5,476	$65,762	100	0	
		10.0			CC	$168,318	$2.41	$9,496	$5,000	0	10,468	8,760
	1	10.0		0.0625	CC	$173,186	$2.48	$9,595	$8,156	0	10,467	8,759

Fig.21. Techno-economic optimized results of feasible configurations for Vellore

Fig.22 displays cash flow as a stacked bar by components, with a different colour representing each of the components in the system. Each bar in the graph represents either a total inflow or total outflow of cash for a single year. The first bar, for year zero, each stacked bar represents the volume of cash flow for that particular component. Negative bars represent an outflow, or expenditure for fuel, equipment replacements, or operation and maintenance (O&M). Positive bar represents an inflow, which is the income from the salvage value of Generator at $4,895 at the end of the project lifetime.[10]

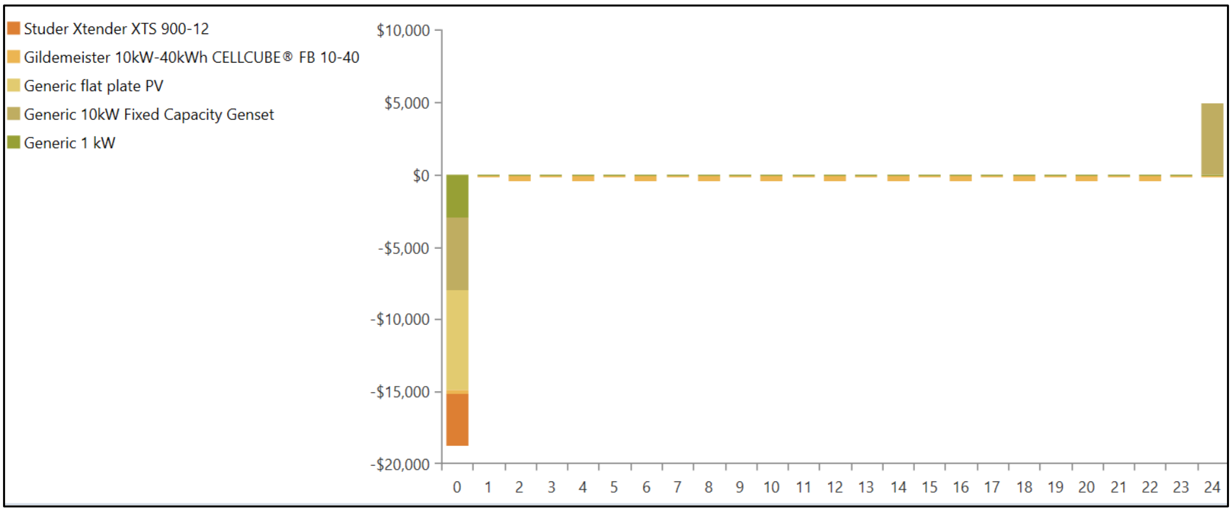
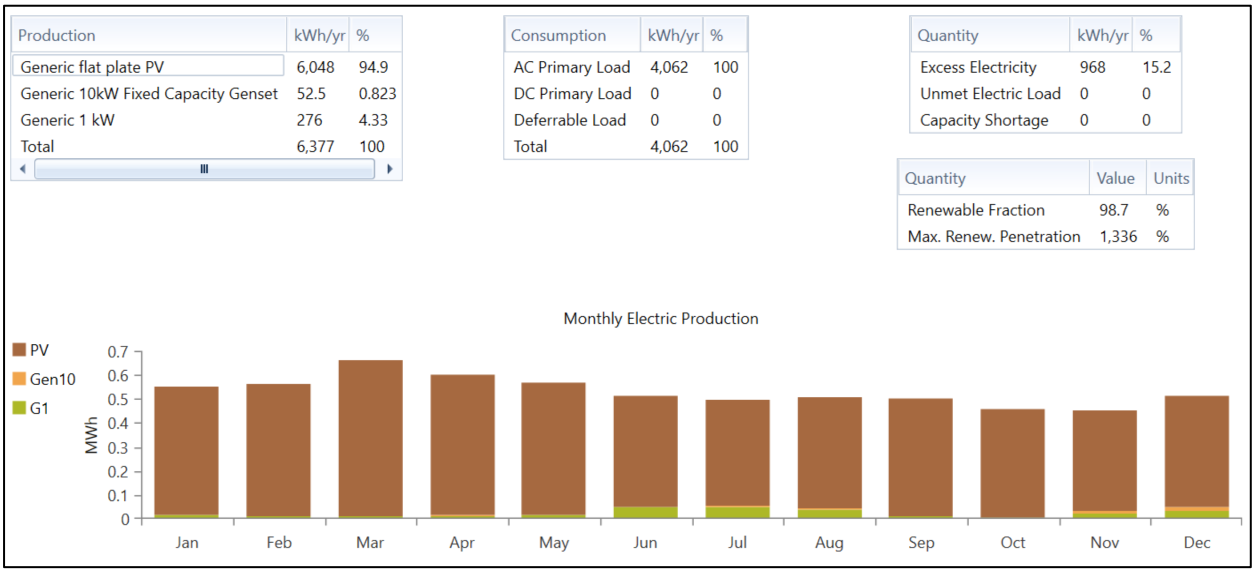


Fig.22. Cash flow by components



Production	kWh/yr	%
Generic flat plate PV	6,048	94.9
Generic 10kW Fixed Capacity Genset	52.5	0.823
Generic 1 kW	276	4.33
Total	6,377	100

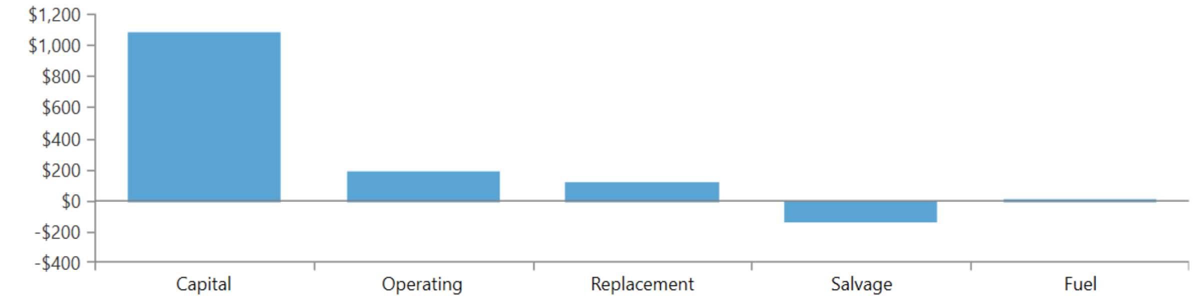
Consumption	kWh/yr	%
AC Primary Load	4,062	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	4,062	100

Quantity	kWh/yr	%
Excess Electricity	968	15.2
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	98.7	%
Max. Renew. Penetration	1,336	%

Fig.23. Monthly electric production

The **Fig.23** shows details about the annual production and consumption of electrical energy by the system on monthly basis.[5] The brown area imply the PV generated power, orange imply generator and green imply wind energy.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1 kW	$174.43	$0.00	$100.00	$0.00	$0.00	$274.43
Generic 10kW Fixed Capacity Genset	$290.71	$0.00	$6.30	$12.55	-$144.75	$164.81
Generic flat plate PV	$401.77	$0.00	$32.14	$0.00	$0.00	$433.91
Gildemeister 10kW-40kWh CELLCUBE® FB 10-40	$16.28	$129.75	$40.00	$0.00	$0.00	$186.03
Studer Xtender XTS 900-12	$208.91	$0.00	$14.37	$0.00	$0.00	$223.28
System	$1,092.10	$129.75	$192.81	$12.55	-$144.75	$1,282.45

Fig.24. Cost summary by cost type

The **Fig.24** displays cost summary by cashflow in annualised value categorised by cost Type. The replacement cost $129.75 is incurred by battery only since lifetime of the high-capacity battery is 2 yrs. only. Note that less money $12.33 was expended on fuel resources because of the consumption and operation of the 1 generator with annual fuel consumption 25.1L/yr. The large costs, according to **Fig24.** came from solar PV $433.91/yr. Solar PV total cost was also high because of the initial investment cost, while the O&M annual cost is very low $32.14. Maintenance cost is highest in case of wind turbines $100 annually was simply due to the high cost incurred during the maintenance of the turbine's moving parts. The replacement costs were relatively small, as the wind turbine lifetime, PV panels lifetime and converter exceeded the system's lifetime; hence, no money was spent on replacing these components.[9] Since running hours of diesel generator is optimised to low value 21 hrs /year to keep renewable factor 98.7% high, there was no need to replace generator during project lifetime.

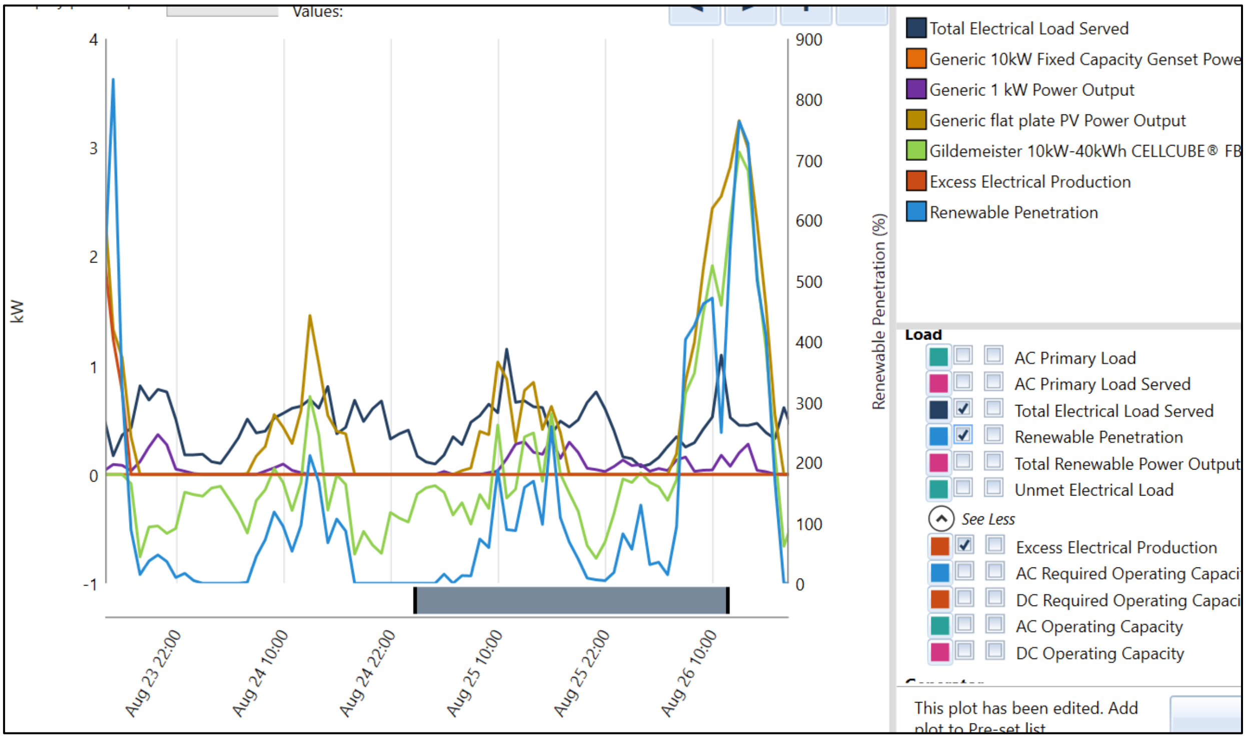


Fig.25. Hourly time series plot

The hourly time series plot is displayed in **Fig.25** views the power generation from each component, how it served the load, the resources that power the components, as well as a number of key operational characteristics from each component for an entire year of your simulation. **Fig.25** depicts the real-time energy scheduling of generation and consumption across four days (August 23-26) Initially, on August 23 at 2200, AC load demand is high and wind power generation fulfils it completely and extra demand is compensated by the battery. Until August 24 at 1000, load demand is continuously decreasing due to off-peak hours until morning. During this time the PV generates power to meet the load and excess production is used to charge the battery. Same is the case until Aug 25 at 2200.As it can be seen diesel generator is not used in this complete time series, all loads are met my renewable sources only. On August 26 at 1000, extra PV power is utilized to charge the battery packs and battery SOC is improved to a higher value.

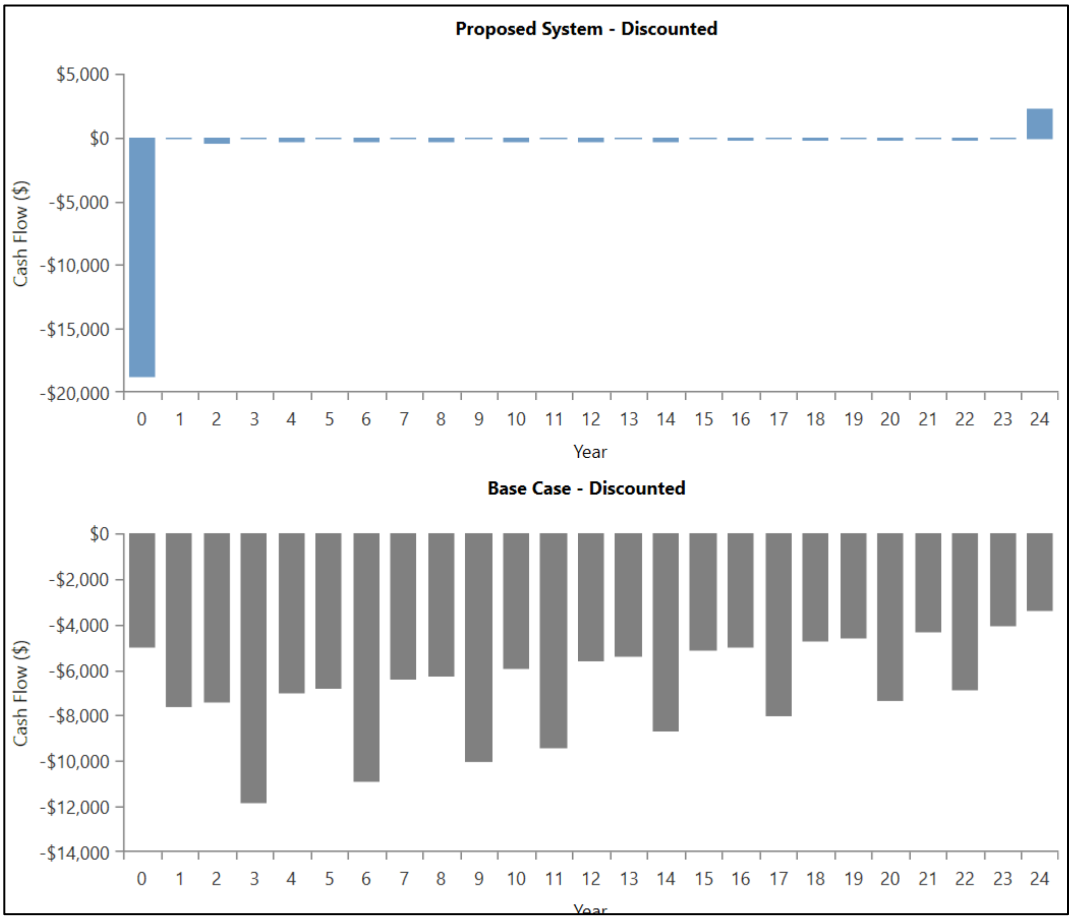


Fig.26. Discounted cash flow results

Fig.26 depicts nominal cash flow for the basic case (diesel only) and optimal case over a 24-year period (wind-battery-PV-DG). Throughout the project's lifespan, the cash flow for the optimal case is kept at a minimum constant, while the value for the base case is steadily increasing.[8] The usage of a diesel plant for electricity generation is especially frequent in isolated rural locations where there is no grid power supply or when the utility grid's energy supply is inconsistent. [6,8]

According to the results of the analysis, this system was the most cost-effective system with the lowest initial cost $5000 of all the configurations evaluated. Its cost-effectiveness was primarily determined by the price of diesel. Furthermore, no renewable energy resources with high installation costs were included in its configuration, making the system less expensive to deploy.

	Architecture										Cost	
						PV (kW)	G1	Gen10 (kW)	Gild10-40	XTS 900-12 (kW)	NPC ($)	Initial capital ($)
Base system								10.0			$168,318	$5,000
Proposed system						3.21	1	10.0	1	1.44	$22,057	$18,783

Metric	Value
Present worth ($)	$146,261
Annual worth ($/yr)	$8,504
Return on investment (%)	63.7
Internal rate of return (%)	61.8
Simple payback (yr)	1.83
Discounted payback (yr)	1.91

Charts...

Fig.27. Comparison of base and proposed system economics

The **Fig.27** shows economic measures representing the value of the difference between the two systems. The difference between the net present costs of the base case system and the current system is the present worth. A positive score shows that the existing approach saves money over the course of the project as compared to the baseline.[8] The discount rate at which the base case and current system have the same net present cost is known as the internal rate of return (IRR). HOMER computes the IRR by computing the discount rate that equals the present value of the difference between the two cash flow sequences [12].

Payback is the length of years it takes for the cumulative cash flow of the difference between the current system and the base case system to turn positive.[12] The payback period reflects how long it will take to recoup the difference in investment expenses between the current and base case systems.[12] The Simple payback 1.83 yrs. is defined as the point at which the nominal cash flow differential line crosses zero. The discounted payback 1.91 yrs. are the point at which the discounted cash flow differential line intersects zero.

Chapter 7

Conclusion and Future scope

A method for optimal sizing of hybrid renewable energy system comprising of PV/Wind turbine/Battery/Diesel generator based on grey wolf optimizer (GWO) is presented. The primary goal of the optimization problem is to reduce the Cost of energy (COE) and LPSP of the system and to determine the number of PV panels, diesel generators, wind turbines, and autonomous days.[15] The simulation was based on wind speed, ambient temperature, and sun irradiance data gathered from the NASA prediction of world-wide energy resources over a one-year period. Findings show that, GWO performance in find the optimal sizing of the renewable system outweighs other meta-heuristic algorithms in finding the optimal solution. The GWO approach can achieve global optimal with relatively modest calculation requirements. The optimal system configuration consists of 21 panels of 0.275 kW each, 5 wind turbines each of 1kW and 1 diesel generator of 4 kW. PV contributes 27 % of the load demand followed by wind energy, battery and diesel at 22%, 27% and 24% respectively. Furthermore, the cost of energy (COE) of the system design achieved was nearly 0.31094 ($/kW) and LPSP (0.043446) which is approximately 0. It is possible to infer that the suggested algorithm has significant merit in solving the optimal design problems of hybrid renewable energy systems and can also be implemented in many other domains.

Since diesel generator is applied, we can implement emission penalties and limit on carbon emission in optimization problem. More efficient and updated cost analysis inputs of the components can be implemented in the simulation process.

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Curriculum vitae

Name	:	KUNAL CHANDA
Father’s name	:	SOUMITRA CHANDRA
Date of Birth	:	12-06-2000
Nationality	:	INDIAN
Sex	:	MALE
Company placed	:	Wipro, RIL
Permanent Address	:	Burdwan, West Bengal
Phone Number	:	+91 7000-306-847
Email Id	:	kunal.chandra2018@vitstudent.ac.in

CGPA: 8.14

Examinations taken:

1. GRE: -----------
2. TOEFL: --------------
3. CAT: ------------

Curriculum vitae

Name	:	YANDRA MOHITH SAI
Father’s name	:	Y.V.P. KUMAR
Date of Birth	:	07-07-2001
Nationality	:	INDIAN
Sex	:	MALE
Company placed	:	-
Permanent Address	:	Tirupati, Andhra
Phone Number	:	+91 6303-875-346
Email Id	:	yandramohithsai@gmail.com

CGPA: 7.82

Examinations taken:

1. GRE: -----------
2. TOEFL: --------------
3. CAT: ------------

Capstone Project

Project Title	Design & Economic Analysis of a Standalone Hybrid Renewable Energy System using Grey Wolf Optimizer
Team Members (Names and Reg Nos.)	Yandra Mohith Sai – 18BEE0255 Kunal Chandra - 18BEE0246
Faculty Guide	Prof. Jayabarathi T
Semester / Year	**VIII / IV Year**
Project Abstract	The GWO algorithm is applied to determine the optimal system configuration and minimize the cost of power generation system in remote area.
Project Title	Design & Economic Analysis of a Standalone Hybrid Renewable Energy System using Grey Wolf Optimizer
List **codes** and **standards** that significantly affect your project. **(Must)**	The specified standards for inverters are IS 16221 (Part 2): 2015 (Safety of Power Converters for use in Solar Photovoltaic Power Systems) IS 16169:2014(Test Procedure of Islanding Prevention Measures for Utility–Interconnected Photovoltaic Inverters). registration from Bureau of Indian Standards (BIS),
List at least two significant **realistic design constraints** that are applied to your project. **(Must)**	On a residential House: - Number of PV Panels: - 45 Number of Diesel Generators: - 4 Number of Wind Turbines: - 5
Briefly explain two **significant trade-offs** considered in your design, including options considered and the solution chosen **(Must)**	**1.** We considered number of houses as variable in our designing so that though initial cost of renewable energy source component appears high but the net cost to individual family is low enough to afford and considerable for investment. **2.** We have reduced the iteration and search wolves to reduce MATLAB simulation run time but higher wolves and iteration may provide finer results than ours.
Describe the **computing aspects, if any,** of your project. Specifically identifying **hardware-software**	**1.** For the GWO algorithm, there is need for production of random real values between the boundary limits. Random number generation is faster in MATLAB than others such as Python, JAVA, etc. **2.** HOMER Energy's HOMER Pro® microgrid software is the global standard for microgrid design optimization in all sectors,

trade-offs, interfaces, and/or interactions	from village electricity and island utilities to grid-connected campuses and military locations. HOMER (Hybrid Optimization of Multiple Electric Renewables) is a programme that makes evaluating designs for both off-grid and grid-connected power systems easier. These selections are complicated by the enormous number of technology options, cost variations, and energy resource availability. The optimization and sensitivity analysis techniques in HOMER make evaluating the many different system configurations a lot easier.