OPTIMIZATION OF A RENEWABLE ELECTRICITY SUPPLY SYSTEM FOR IIT KHARAGPUR

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Bachelor's Thesis Project Report

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ACKNOWLEDGEMENT

I want to acknowledge the constant guidance and feedback provided throughout the project by my supervisor, Prof. Sri Krishna Kumar, Dept. of Industrial and Systems Engineering, IIT Kharagpur who gave me the opportunity to work on this exciting project and without whose advice, the project would be very difficult to complete.

CERTIFICATE

This serves as proof that Debraj Chatterjee, 19IM10039 has done his Bachelor's Thesis Project (BTP) on the topic 'Optimization of a Renewable Electricity Supply System for IIT Kharagpur' in the Autumn Semester of 2022 within the Department of Industrial and Systems Engineering.

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ABSTRACT

In the recently concluded COP 27 Summit, India made ambitious initiatives to support its climate targets including **"promoting the usage of renewable energy, e-mobility, ethanol-blended fuels and green hydrogen as an alternate energy source".**

The world is taking climate change seriously and India is not far behind even though it is in the category of developing nations. India wants to use the renewable and green energy boom to its advantage and develop using them instead of relying on traditional fossil fuels.

Despite releasing **less than 4%** of the world's total carbon emissions, India is taking stringent measures to curb its carbon emissions. With initiatives such as **FAME** (**F**aster **A**doption and **M**anufacturing of **E**lectric Vehicles), and global coalitions such as the one with International Solar Alliance.

In this regard, one of the major usages of fossil fuels and coal occurs in the generation, transmission, and distribution of electricity. The generation of electricity is responsible for **40%** of all the emissions, although only **20%** of the total energy is finally converted into electricity. This means that electricity generation from coal and fossil fuels is one of the most wasteful and polluting practices. Yet, India is heavily reliant on coal for its electricity generation needs**. 80%** of electricity generated in India comes from coal-based thermal power plants. This is a characteristic of most developing nations.

In the light of this, it is important to make a shift to renewable energy for electricity generation and supply, and what better place than IIT Kharagpur to start with, which is nothing less than a small ecosystem on its own! This project aims at coming up with an optimized renewable electricity supply system for IIT Kharagpur.

LITERATURE REVIEW

First of all, the domain of sustainability and renewable energy was chosen by me out of interest. Several research papers that were in the conjunction of Industrial and Systems Engineering and its applications in sustainability were explored. A strong focus was put on scope of optimization in the project due to prior experience in the methodology, and potential to be applied to a wide array of problems.

The different research papers were prioritized based upon relevance to the subject and domain of interest. Research papers about finance, optimization, computer vision techniques were explored, however most of them did not capture the kind of impact that I wanted to create with my Bachelor's Thesis Project.

Finally, I came across a research paper titled – ***"Research on the configuration and operation effect of the hybrid solar-wind-battery power generation system based on NSGA-II"*** *by Zhang et al.* that was published in the **'Elsevier' Journal** under the domain of Energy.

The research paper piqued my interest because of my love for renewable energy and how it was creating a quantitative impact by the optimization of a renewable energy system. Moreover, the paper had applied the multi-objective optimization algorithm **NSGA-II (Non-Dominated Sorting Algorithm – II).** This further excited me because we had been taught evolutionary-search based optimization algorithms in an earlier course 'Optimization and Heuristic Methods'.
I also had done 2 projects in single-objective optimization using evolutionary-search algorithms namely **'Differential Evolution Algorithm'** and a novel hybrid evolutionary algorithm **'Colony of Genetic Artificial Bees (CoGAB)'**, formulated by me.

Therefore, the application of a multi-objective evolutionary-search based optimization algorithm seemed to be the most logical next progression. The single most popular multi-objective evolutionary-search based optimization algorithm is

NSGA-II, developed by **Dr. Kalyanmoy Deb**, who is an alumnus of IIT Kharagpur itself, and has done pioneering work in multi-objective optimization and genetic algorithms. His original paper on the algorithm is the most cited paper coming out of the Indian research space. This served as extra motivation for applying the algorithm.

Coming to the research paper in question, it is an attempt to create an optimized hybrid solar-wind-battery energy supply system on a remote island in China. The power supplies required for the DC and AC power loads have been summed up and the optimal configuration of the system has been decided based upon two conflicting objectives – **(1) Total System Cost, and (2) Loss of Power Supply Probability (LPSP).**

The **3 decision variables are – (1) Number of windmills, (2) Number of photovoltaic array modules, and (3) Number of battery packs** that must be installed. The objectives are conflicting because by increasing the number of windmills or photovoltaic arrays, the electricity generation capability of the system increases – this means that there is lesser probability of loss of power supply. Therefore, objective (2) of LPSP decreases. However, at the same time installing more windmills and/or photovoltaic cells means incurring a greater setup and maintenance cost, and hence objective (1) increases. Since, the goal is to minimize both objectives (1) and (2), and by improving upon objective (2), objective (1) worsens, **it can be concluded that objectives (1) and (2) are conflicting in nature.** This conflicting nature of objectives is the essence of multi-objective optimization and a perfect situation for the use of NSGA-II.

The research work in the paper is also unique in the sense that it not only proposes an optimal configuration but also implements the same physically to verify the results, giving increased insights about the theory. Other works in this domain have not verified the accuracy of their proposed optimal configuration and relied on simulations. However, by implementing the proposal in reality, the research has gone one step further.

The implementation was done on a remote island in China. This makes it a suitable precursor for the application of the same in the IIT Kharagpur campus given the remote location of IIT Kharagpur campus compared to other mainstream IITs and the large available area to construct a full-fledged system. The weather conditions in China and India are also similar given their broadly similar locations in the world geographic map, which increases the chance of a successful adaption of the model for the IIT Kharagpur campus.

PROJECT PROPOSAL

The project proposal is to implement a hybrid solar-wind energy system for the IIT Kharagpur campus. In the original research paper, the island is completely remote and devoid of any form of on-grid electricity supply. Therefore, a hybrid solar-wind-battery energy supply system is implemented, where in case of inadequate energy generation the batteries take over. Energy is also stored in the battery. This is similar to having a backup on-grid electricity supply system. However, IIT Kharagpur is not that remote and receives adequate on-grid electricity supply.

The motivation here is to make a gradual reduction in the dependence on on-grid electricity supply and not completely eliminate it, which is impossible, at least in the short term. Hence, for the purpose of this project, optimization is done for only solar modules and windmills and energy is not stored in a battery. Failure is considered when the electricity generation from the setup is not adequate and we have to fall back on the on-grid supply.

IIT Kharagpur has already tried to make a shift to renewable energy electricity generation with an initial **1.1MW on-grid connected solar energy project with an estimated cost of Rs. 69.8 million or $970,000 [4].** A further 5.5MW solar project is in the works.

However, the performance of the solar project has not been satisfactory. Though, a lot of maintenance is done daily to keep them running in optimal condition, their supply of electricity is not adequate. This can be observed first hand from the dark stretches of roads in front of the Rajendra Prasad (RP) and Radhakrishnan (RK) Halls of Residences, where the street lights have been replaced by solar-powered street lamps, which seldom work. A similar situation can also be observed in front of the Nalanda Classroom Complex where all the cycle sheds have been converted into solar panels but the adjoining solar street lamps often work erratically. This has led to the Nalanda Classroom Complex roads to become pitch dark as soon as sunset happens. Photos of the same are shown below –

A non-functional solar street lamp in front of Nalanda

The roads in front of Nalanda are usually pitch dark after sunset

A dark stretch of road in front of RP Hall of Residence

A brief about the different steps followed in the project are as follows –

1) **Domain Selection, Literature Survey, and Project Proposal:**
   The domain of the project was chosen to be a mix of sustainability, renewable energy systems, and optimization out of interest for the same. Sufficient literature survey was made to understand about the existing and upcoming work happening in the domain. Finally, a suitable project was chosen based upon (1) the impact it could create and (2) the need for the same. The project proposal was finally sent to and approved by the supervisor.

2) **Data Collection:**
   The requirement of Data was done by taking cues from the data used in the original research paper and adapting the same for IIT KGP's scenario, and the

project proposal. Most of the data was obtained from reliable and official sources from the institute. However, some sensitive data was not shared and thus, had to be estimated.

3) **<u>Modelling:</u>**

Based upon the extensiveness of the data collected and the models used in the research paper, an adapted model was created. The model also had unique points pertaining to the IIT KGP campus, such as ‘on-semester months’ and ‘off-semester months’ signifying the months when the students are actually in campus and the months when they usually go home.

4) **<u>Algorithm Coding:</u>**

The whole algorithm coding was done on python due to familiarity with the language and availability of extensive libraries for multi-objective optimization and visualization. The ‘**pymoo**’ (standing for **Py**thon **M**ulti-**O**bjective **O**ptimization) library was used for implementing the NSGA-II algorithm due to the efficient way the algorithm has already been set up within the library.

5) **<u>Results and Reporting:</u>**

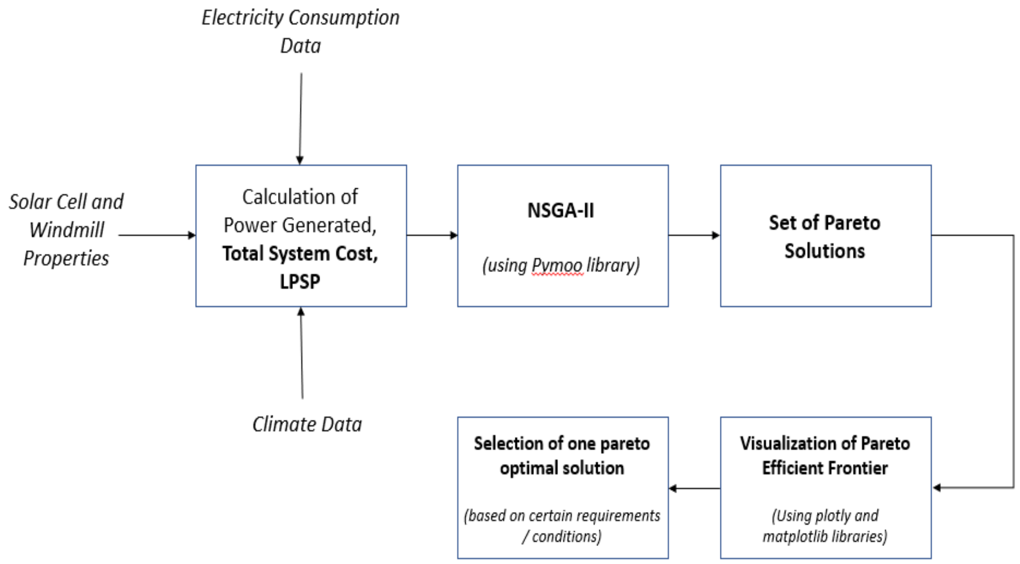
After running the algorithm on the model, the results were gathered and organized, and inferences made. Visualization libraries ‘**plotly**’ and ‘**matplotlib**’ were used to visualize the results and their characteristics such as the **Pareto efficient frontier**. Based upon the results and the inferences drawn, a pilot recommendation was made and also the gaps in the model were discovered. Some of the gaps were filled in further iterations and others being out of the available time scope of the project were included in the ‘**future scope**’ of the project.

METHODOLOGY

1) Model Overview -

The whole model is based upon taking inputs in the form of (1) Kharagpur climate data for each period, (2) Electricity Consumption Requirement for each period, and (3) Windmill and Photovoltaic Cell Properties (Costs and Power Generation Capability). Based on these inputs, the total power generation in each period and total system cost is calculated. The loss of power supply probability is determined by comparing the electricity power consumption requirement and the generation. This gives the two objective function values for the decision variable set of (number of windmills, number of solar panels). NSGA-II is then run on this to come up with a set of pareto-optimal solutions.

A schematic describing the same is as follows –

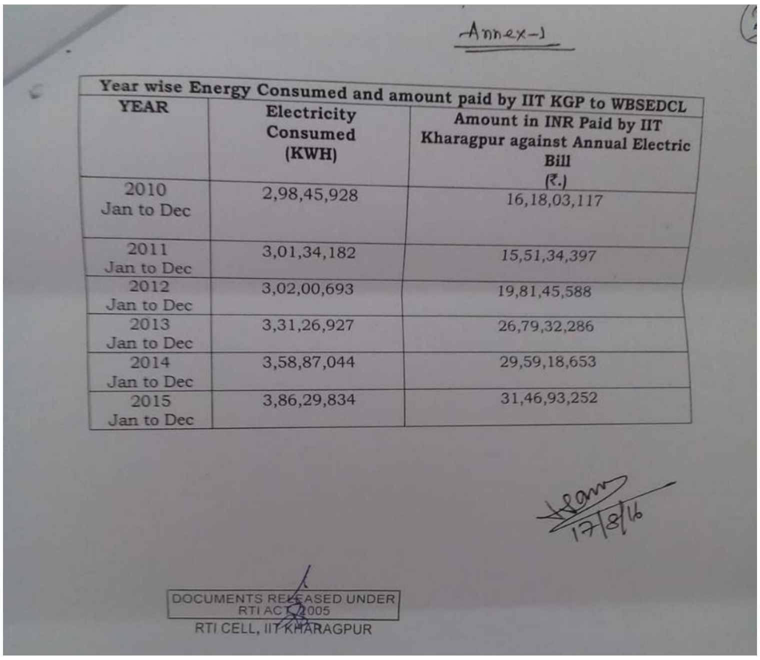


2) Data Collection –

a. <u>Electricity Consumption Data: -</u>

Electricity consumption and spend data for the entire IIT Kharagpur campus was available for the years **2010-2016**. This was available through a **RTI (Right to Information)** that was filed seeking information about the same.

The screenshot of IIT Kharagpur's response about the data request is as follows -

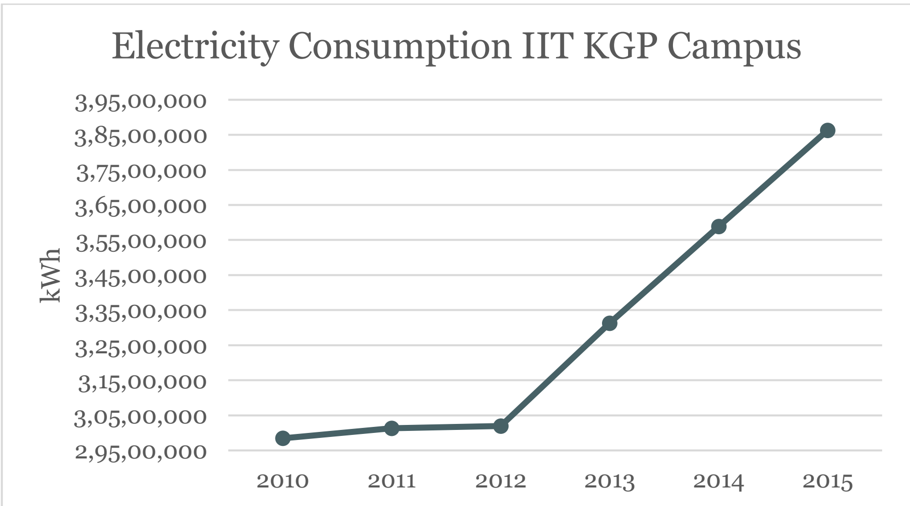


Annex-I

Year wise Energy Consumed and amount paid by IIT KGP to WBSEDCL		
YEAR	Electricity Consumed (KWH)	Amount in INR Paid by IIT Kharagpur against Annual Electric Bill (₹.)
2010 Jan to Dec	2,98,45,928	16,18,03,117
2011 Jan to Dec	3,01,34,182	15,51,34,397
2012 Jan to Dec	3,02,00,693	19,81,45,588
2013 Jan to Dec	3,31,26,927	26,79,32,286
2014 Jan to Dec	3,58,87,044	29,59,18,653
2015 Jan to Dec	3,86,29,834	31,46,93,252

17/8/16

DOCUMENTS RELEASED UNDER RTI ACT 2005
RTI CELL, IIT KHARAGPUR



The data from 2010 – 2016 was plotted as shown above. It can be seen that after 2012, the electricity consumption follows a very linear path. The linear data from 2019 onwards would be an outlier due to the Covid-19 pandemic and subsequent online mode of study. Hence, the data from 2012-2015 is used to fit a linear model and forecast the electricity consumption for 2025. The project is conducted for 2025 because of the assumption that it would take at least 3 years for the installation of the recommended renewable energy electricity supply system. The forecasted electricity consumption for **2025 is 66,715,796 kWh.**

This is the total electricity consumption for the year. However, we know that during the months of May, June, July, and December students go home. Hence, electricity consumption during that time will be low. Also, electricity consumption during the winter months would be lower than that during the summer months as fans and ACs are not running. Taking into consideration all these logical reasons it has been assumed that the **Autumn Sem months (August, September, October, November) constitute 50%** of the total consumption, the **Spring Semester months (January, February, March, April) constitute 40%** of the total consumption, whereas the **off months (May, June, July, December) constitute the remaining 10%** of the total annual electricity consumption.

Time	% of total electricity consumption
Jan, Feb, March, Apr	40%
Aug, Sep, Oct, Nov	50%
May, Jun, Jul, Dec	10%

Also, another logical assumption has been taken that **during the day time, 70% of the total electricity consumption occurs** whereas during the **night, the rest 30% occurs**. Day is considered to be 7am - 7pm here and that is the time when all the classes occur. Therefore, it is logical that more electricity consumption from running fans, lights, ACs, projectors, etc. occur.

730 periods are considered in a year (2 periods daily for 365 days). The **daily electricity consumption is equal to the monthly consumption divided by the number of days.** This number is then divided into the day-time consumption and the night-time consumption. This finally led to the electricity consumption in kWh for the 730 periods.

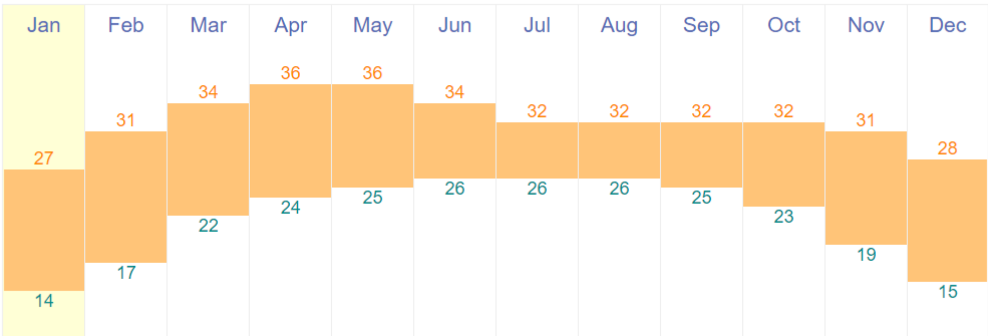
$$Daily\ Electricity\ Consumption = \frac{Monthly\ Electricity\ Consumption}{Number\ of\ Days\ in\ the\ Month}$$

b. Kharagpur Climate Data: -

Climate data points on the following factors had to be collected –
(1) Ambient Temperature, (2) Solar Intensity, (3) Wind Speed.

(1) Ambient Temperature -

The ambient temperature during each period was calculated based upon the maximum and minimum temperature observed in the month. The maximum temperature was assigned to the daytime and minimum to the night time period, which is a fair assumption to make. The data was taken from a well reputed temperature database [5].



Monthly Maximum and Minimum Temperature

(2) Solar Intensity -

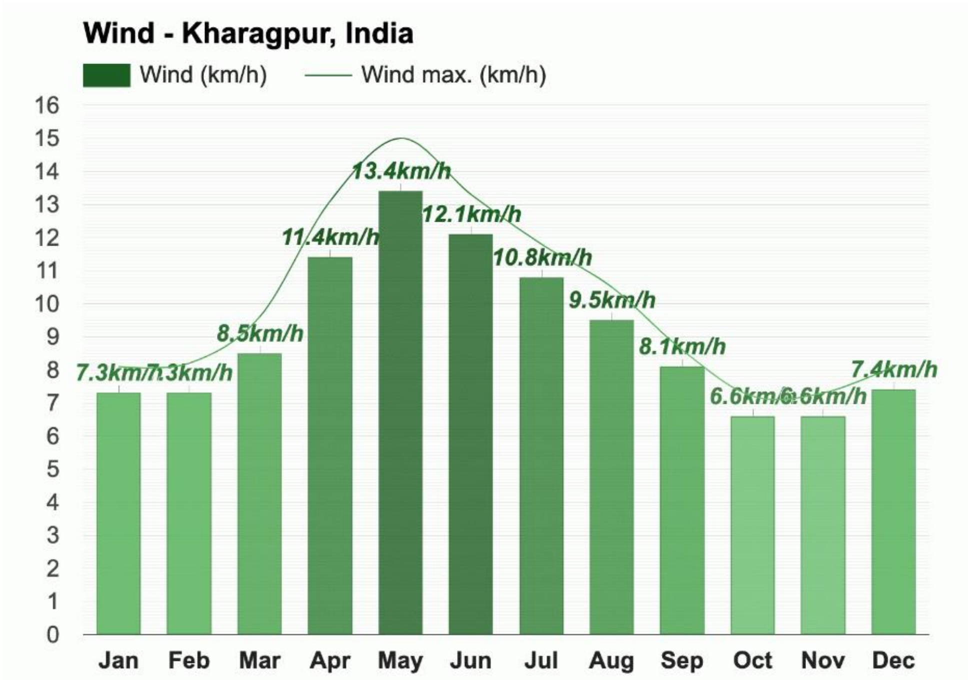
The solar intensity was calculated for each day of the year based upon the latitude and longitude of Kharagpur and the expected orbit and inclination of the earth using equations from "Renewable and Efficient Electric Power Systems" by Gilbert Masters Chapter 7.

The solar intensity during the night time period was 0 watts/m^2.

A visualization of the daily changing solar intensity can be found here[6]

(3) Wind Speed -

The maximum average wind speed and the average wind speed was recorded. The wind speed during the night was considered to be the maximum average wind speed while half of the average wind speed was considered to be the speed during the day, which is a fair assumption to make since wind is strong during the night time period after sunset and just before sunrise. The data for the same was collected from here [7]



Final Pre-Processed Weather Dataset					
Month	**Night Time Temperature (^{0}C)**	**Day-Time Temperature (^{0}C)**	**Day-Time Wind Speed (km/hr)**	**Night-Time Wind Speed (km/hr)**	**Solar Intensity (W/m^2)**
January	14	27	3.65	8	725.5
February	17	31	3.65	8.3	808.5
March	22	34	4.25	9	893.5
April	24	36	5.7	13	939.5
May	25	36	6.7	15	940.5
June	26	34	6.05	13.5	928.5
July	26	32	5.4	11.8	925.5
August	26	32	4.75	10.2	924.5
September	25	32	4.05	8.6	894
October	23	32	3.3	7	821
November	19	31	3.3	7.5	736.5
December	15	28	3.7	8.2	694

c. **<u>Windmill and Solar Panel Properties: -</u>**

The properties of the wind turbines and the solar panels have been taken from commonly available solutions in India, and those that matched relatively with the ones used in the original research paper. The tables outlining their properties are given below –

AC WIND TURBINE PROPERTIES		
Property	**Symbol**	**Value**
Rated Power (kW)	$P_{W,r}$	6
Cut-in Speed (m/s)	V_{cut-in}	2.5
Rated Wind Speed (m/s)	$V_{rated-in}$	10
Cut-out Speed (m/s)	$V_{cut-out}$	65
Investment Cost ($/kW)	IC_W	520
Maintenance Cost ($/yr)	MC_W	30

SOLAR PHOTOVOLTAIC CELL PROPERTIES		
Property	**Symbol**	**Value**
Rated Power (kW)	$P_{pv,r}$	0.1
Derating Factor (Dust)	f_{pv}	0.9
Standard Solar Radiation Conditions (W/m^2)	G_{stc}	1000
Temperature Influence Coefficient (1/^{0}C)	α_t	-0.0037
Standard Temperature (^{0}C)	T_{stc}	25
Normal Operating Cell Temperature (^{0}C)	N_{oct}	45
Investment Cost ($/kW)	IC_{pv}	350
Maintenance Cost ($/yr)	MC_{pv}	2.5

3) Defining the Optimization Problem –

- Electricity power generation in a period t is the sum of the total electricity generated by the wind turbines and the solar panels.
- Total system cost (TSC) is the sum of installation and maintenance costs for all the solar cells and wind turbines.

<u>Equation for power generated by a solar cell in a period –</u>

$$T = T_a + \frac{NOCT - 20}{800} G_{STC}$$

$$P_{pv}(t) = f_{pv} P_{pv,r} \frac{G}{G_{stc}} (1 + \alpha_t (T - T_{stc}))$$

<u>Equation for power generated by an AC wind turbine in a period –</u>

$$P_w(t) = \begin{cases} 0, & V < V_{cut-in} \\ P_r\left(\frac{V^3}{V_r^3 - V_{cut-in}^3}\right) - P_r\left(\frac{V_{cut-in}^3}{V_r^3 - V_{cut-in}^3}\right), & V_{cut-in} \leq V < V_{rated} \\ P_r, & V_{rated} < V \leq V_{cut-out} \\ 0, & V > V_{cut-out} \end{cases}$$

Decision Variables –

(1) Number of AC wind turbines, $N_{w,}$

(2) Number of Solar PV Cells, N_{pv}

Equation for total power generated in a period –

$$P(t) = (N_w \times P_w(t) \times \eta_{con}) + \ (N_{pv} \times P_{pv}(t) \times \eta_{con} \times \eta_{inv})$$

Where η_{con} = convertor efficiency = 0.95

η_{inv} = inverter efficiency = 0.95

Equation for Loss of Power Supply (LPS) Indicator in a period –

$$LPS(t) = 1, if\ P(t) < D(t)$$

$$0, otherwise$$

Where D(t) = Electricity Power Demand in period t

Objective Functions –

(1) Total System Cost (TSC): (To be minimized)

$$IC = (6 \times N_w \times IC_w) + \left(0.1 \times N_{pv} \times IC_{pv}\right) \quad \text{(Implementation Cost)}$$

$$MC = (N_w \times MC_w) + \left(N_{pv} \times MC_{pv}\right) \quad \text{(Maintenance Cost)}$$

$$TSC = IC + MC \quad \text{(Total System Cost)}$$

(2) Loss of Power Supply Probability (LPSP): (To be minimized)

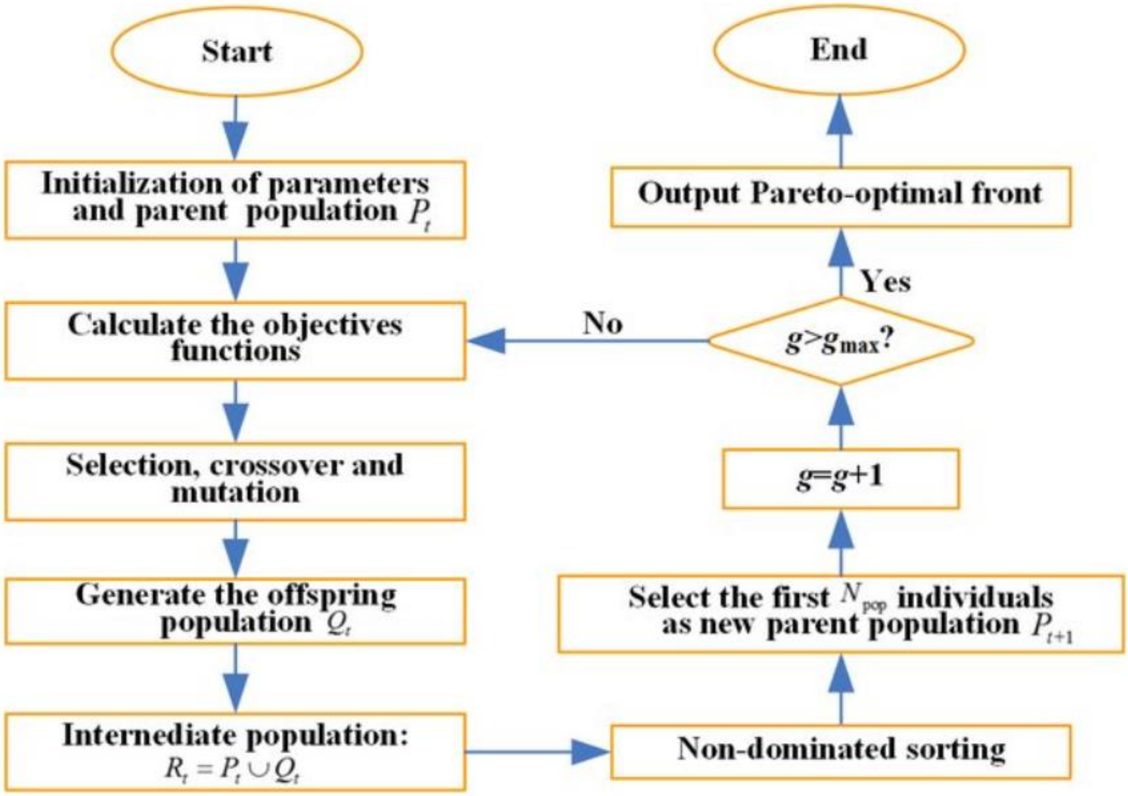
$$LPSP = \frac{\sum_{t=1}^{n=730} LPS(t)}{\sum_{t=1}^{n=730} t}$$

Constraints –

$$N_w, N_{pv} \geq 0$$

On this optimization problem, the NSGA-II or Non-Dominated Sorting Genetic Algorithm – II was applied. The general flowchart of the same is shown below -

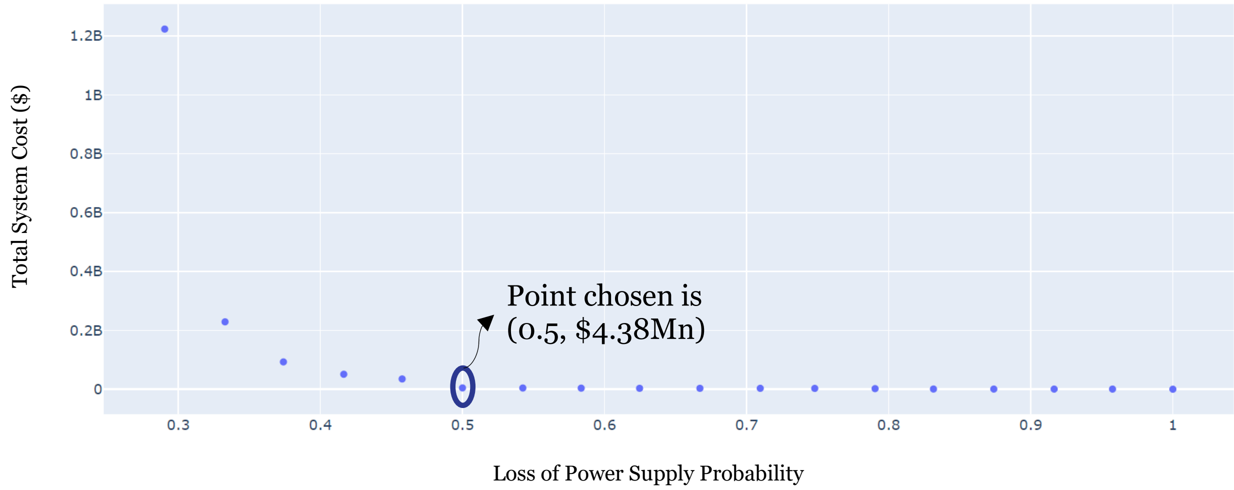
Flowchart of the NSGA-II algorithm



This algorithm was implemented using the ready-made NSGA-II algorithm in the **pymoo** library.

RESULTS AND DISCUSSION

The algorithm was run for 100 generations and a set of Pareto Optimal Solutions were obtained. The Pareto Optimal Frontier obtained is as follows -



The pareto optimal solution chosen is the point corresponding to objective function values (0.5, $4.38Mn). This means that 50% of the electricity supply will be from the renewable energy setup.

To achieve this the values of the decision variables come out to be

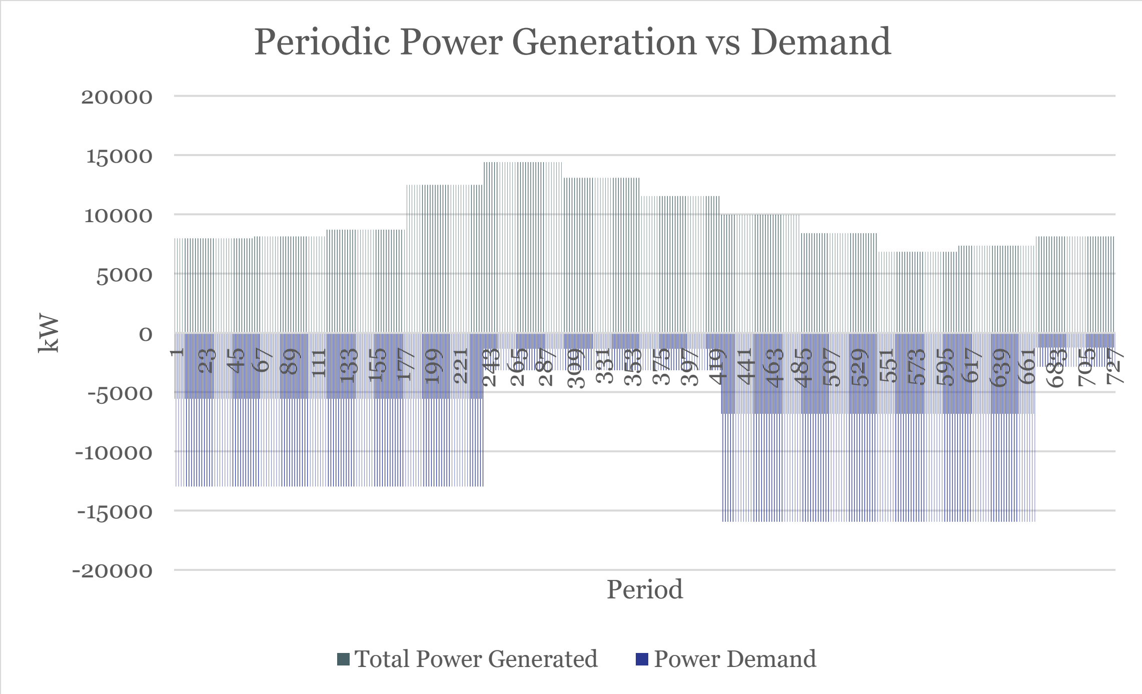
- **Number of wind turbines = 1**
- **Number of solar panels = 974**

The **annual savings** in electricity cost after subtracting the maintenance costs are $3,104,613.37 or **$3.1Mn.**

Therefore, the **breakeven period** for the initial investment will be ($4.38Mn/$3.10Mn) = **1.32 years**

Given the massive potential savings and short breakeven period, this project can be surely undertaken, however there are certain limitations with the analysis which have been discussed further.

Based on these optimized values for the number of solar panels and wind turbines, the graph for the periodic power generation vs power demand is as follows -



LIMITATIONS AND FUTURE SCOPE

- The main limitation in the analysis was the lack of accurate periodic data. Ideally, the analysis should have been done for hourly time periods with accurate hourly data available. However, due to the unavailability, the period size has been enlarged and also some assumptions have been taken.

- The implementation costs are representative of the price of the setup; however, it is not necessary that these prices are actually available. Other costs such as labor and maintenance also keep on fluctuating.

- Ideally, a multi-year analysis should have been made with maintenance costs being discounted and the electricity consumption taken with a growth rate. However, as an initial pilot, this analysis is indicative of at least the potential benefits of undertaking such a project.

- Massive future scope lies in adding one more element to the system setup, that is batteries. Currently, in the model the power generated in one period is not being stored. However, by the introduction of storage houses in the form of batteries, this problem will be solved. This will potentially remove the reliance on on-grid electricity supply completely.

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