Techno- Economic Feasibility Analysis of Off-grid Hybrid Energy System using Particle Swarm Optimization (PSO)

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I hereby declare that the thesis entitled ***"Techno-Economic Feasibility Analysis of Off-grid Hybrid Energy System using Particle Swarm Optimization (PSO)"*** *contains original research work by the undersigned candidate, as part of Degree of Master of Engineering in Power Engineering studies.*

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Abstract

In this paper an intelligent method is applied to the problem of unit sizing and scheduling in a stand-alone hybrid power system such that the demand of a rural area is met. This study is performed for Laxmijanardanpur village of Sundarban area, West Bengal (India) whose latitude and longitude are 21°46´ and 88°20´ respectively. It is to mention that around the world there is much similar type of remote regions with this typical situation that can be expanded.

Since grid extension has not reached yet to too many remote regions in our country so a large interest regarding to the installation of off-grid power plant based on renewable energy sources has been created. Only solar or wind power system due to their intermittent power generation behavior can't give the reliable solution, hybrid power system which comprises different components or power producers like battery and diesel generator also can be introduced along with the Wind Turbine and Solar PV. First the Solar-Wind-Battery-Dg hybrid system combination is analyzed for the specified load profile of that location during the project life-time and later its performance is stated. After that the system has been optimized with a specific intension or objective to get the minimum net present cost and cost of energy of the system. The emission of carbon dioxide for a single day, for one year, for unit generation from the system has also been calculated and compared to a 60MW coal based thermal power plant.

When the power produced by the Wind Turbine plus power produced by Solar PV array are more than the load demand, the remainder is delivered to the battery and the battery is charged according to the proper charging equation. In contrast, when the power produced by the Wind Turbine plus that produced by the Solar PV array are less than the demand, battery becomes discharged or diesel generators are employed to the system. Our aim is to minimize the total net present cost of the system such that the demand is met and to reduce the emission of Carbon dioxide gas. MATLAB was used to build the dynamic model and simulate the system and PSO algorithm is used to get the optimal sizing and scheduling results of system's components.

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Finally, I would like to express my gratitude to different web-search engines and many who have worked on different combination of standalone hybrid energy system along with the proper optimization procedure, based on which I have been able to prepare my term paper.

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List of Abbreviations

PV	=	Photo Voltaic.
DG	=	Diesel Generator.
HPS	=	Hybrid Power System.
GHG	=	Green House Gas.
PSO	=	Particle Swarm Optimization.
GA	=	Genetic Algorithm.
BCGA	=	Binary Coded Genetic Algorithm.
RCGA	=	Real Coded Genetic Algorithm.
BFO	=	Bacteria Foraging Optimization.
ACO	=	Ant Colony Optimization.
OF	=	Objective Function.
RET	=	Renewable Energy Technology.
SPV	=	Solar Photo Voltaic.
LUCE	=	Levelized Unit Cost of Electricity.
LOLP	=	Loss of Load Probability.
LPSP	=	Loss of Power Supply Probability.
BET	=	Bio Energy Technology.
COE	=	Cost of Energy.
RE	=	Renewable Energy.

EPDF = Electric Power Delivery Factor.

LCC = Life Cycle Cost.

NPC = Net Present Cost.

CDM = Clean Development Mechanism.

LST = Local Solar Time.

NOCT = Nominal Operating Cell Temperature.

DOD = Depth of discharge.

WBREDA = West Bengal Renewable Energy Development Agency.

CWET = Centre for Wind Energy Technology.

T&D = Transportation and Distribution.

O&M = Operation and Maintenance.

Nomenclature

$\bar{G}$ = global horizontal radiation on the earth's surface averaged over the time step [kW/m^2].

$\overline{G_0}$ = extraterrestrial horizontal radiation averaged over the time step [kW/m2].

n = monthly mean daily number of hour of observed sunshine hours.

N = monthly mean value of day length at a particular location.

a & b = climatologically determined regression constant.

$\overline{G_d}$ = monthly mean of the daily diffuse solar radiation [kW/m^2].

$\overline{G_b}$ = monthly mean of the daily beam radiation [kW/m^2].

K_t = clearness index.

G_{on} = extraterrestrial normal radiation [kW/m^2].

G_{sc} = solar constant.

Φ = latitude.

δ = solar declination angle.

θ_z = zenith angle.

ω_s = sunset hour angles.

ω_1 = hour angle at the beginning of the time step [°].

ω_2 = hour angle at the end of the time step [°].

R_b = beam radiation component.

A_i = anisotropy index.

f = final factor.

β = slope of the surface [°].

ρ_g = ground reflectance, which is also called the albedo [%].

Chapter 1: Introduction

1.1. Introduction

Energy demand is directly proportional to the increment of population. So with the gradually increasing world's population, the demand of load energy is also rising. The rising demand can be met with the help of several renewable energy sources, which has taken a huge part in the field of electricity generation. Non-conventional energy sources can also prevent adverse effect of atmospheric pollution. It is found from different statistics and survey which has been made in very recent years that, almost thirty three percent of the world's populations do not have access to electricity [1, 2]. Most of the non-electrified regions are situated in developing countries. These regions can be electrified either by two means- first one by extending the grids of the existing power systems which is nearer to that rural region or by constructing isolated standalone new power systems, which can be made up of either conventional or alternative energy sources or the combination of both. In general, it is preferred to go for the extension of the existing grids but they are not always feasible or affordable because the fact is most of the non-electrified regions in developing countries are located in remote areas, like hilly regions, forests, deserts and islands, which demands huge investment for grid extension.

Due to those above sited problems necessity to go for a hybrid energy system has been increased. Hybrid energy system comprises of different renewable or non-renewable energy sources. All the sources are combined with the specific connection. Renewable sources like Solar PV, Wind Turbine along with the battery and DG as a back-up energy sources can establish a suitable hybrid energy system.

The comparison of capital investment of public grid and PV/Wind/Battery/DG hybrid system are very interesting. The costs, regarding the extension of grid are primarily depend on the distance and thus the investment cost increases according to the distance between the site, which is to be electrified and the main grid system. On the other hand, the hybrid system's installation,

operation & maintenance and replacement costs are mainly dependent on the generation capacity of the source which in turn is related to the load demand by the consumers. Thus, for a small demand, a small investment is needed and for a large demand, a larger investment is needed. The initial investment cost or capital cost of a hybrid power system is higher than the conventional source. But in case of conventional source, the running or variable costs like high fuel cost, transportation cost, replacement cost and maintenance cost throughout its life overshadow its lower initial cost. Though the initial investment for hybrid power systems is high but due to the low running cost and overall life-time cost, it is very much economically viable and attracts users or consumers.

Now a day's a lot of researches are going on to examine this effectiveness of using alternate renewable energy in the field of power generation. These recent researches and developments of alternative energy sources have shown excellent potential. There is a huge potential of renewable energy sources, like solar energy, wind energy, or micro-hydropower to provide a quality power supply to remote areas. The abundant energy available in nature can be harnessed and converted to electricity in a sustainable way to supply the necessary power demand and thus to elevate the living standards of the people without access to the electricity grid.

For remote places where electricity has not reached yet, it is recommended that decentralized generation or standalone generation, which is based on renewable energy technologies, is perhaps the only efficient way to provide electricity. For the conventional energy sources there are so many difficulty arises regarding to the extension of grids, transportation of fuels to the remote regions and replacement parts needed for the system that never comes in case of renewable energy system. Also the renewable energy sources are locally available. Thus, if a system can be designed by non-conventional energy sources along with the conventional one, it can reduce the operating periods of the conventional power sources considerably which will result the reduction of the fuel consumption and minimize the need of maintenance. It will help in the improvement of sustainable power generation.

A system which fully depends upon renewable energy resources is possible but not always reliable for the intermittent nature of the resources. In order to meet the sustained load demands during the varying natural conditions, different energy sources and different combinations of several devices need to be integrated with each other for extended usage of alternative energy.

Thus, the best choice is to use standalone hybrid power systems which are optimally combined with conventional resource, like diesel generator.

1.2. Motivation

In developing countries there are many remote rural regions, where grid connected supply has not reached yet due to high cost of grid extension and many other social and economical reasons. But in those regions available solar and wind energy can be found. Economically inefficiency of conventional energy like fossil fuels and the adverse environmental effects of conventional power generation systems created renewed massive interest in renewable energy sources and leads to a new era towards building a sustainable energy economy. The wind-solar hybrid energy system has become the world's fastest growing energy sources, expanding globally at a rate of 25–35% annually over the last decade [3, 4].

The advantages of using renewable energy sources for the power generation in different rural regions or villages are obvious such as the cost of transported fossil fuels are very much high. Peoples of those regions are not that much economically fit to purchase the fuel. Also the issues of climate change and global warming concern come in case of fossil fuel. That problem can be slightly mitigated by using both renewable and conventional energy in a same system called as hybrid power system. A hybrid power system has the ability to provide 24hour grid quality electricity to the load. This system offers a better efficiency, flexibility of planning and environmental benefits compared to the fully conventional diesel generator stand-alone system. The maintenance costs of the diesel generator can be decreased as a consequence; the efficiency of operation is increased and operational time is reduced which also means less fuel usage. The system also gives the opportunity for expanding its capacity in order to cope with the increasing demand in the future. This can be done by increasing either the rated power of diesel generator, renewable sources or both of them.

The disadvantage of standalone power systems using renewable energy is that the availability of renewable energy sources has daily and seasonal variation which results in difficulties of regulating the output power to cope with the load demand. Also, a very high initial capital investment cost is required. Combining the renewable energy generation with conventional

diesel power generation will enable the power generated from a renewable energy sources to be more reliable, affordable and can be used more efficiently.

This thesis focuses on the combination of wind, solar, diesel generator and energy storing systems like battery for sustainable power generation. The wind turbine output power varies with the wind speed at different conditions. The solar output also varies with the hourly, daily and seasonal variation of solar irradiation. Thus, a generator-set system with a battery bank (energy storage bank) can be integrated with the wind turbine(s) and PV-system to ensure that the system performs very reliably under all conditions.

1.3. Objective

The objective of this project is to make a suitable standalone hybrid system model and simulate it to get the exact optimal sizing and scheduling results of different components of that model, which comprises of renewable energy sources (PV-arrays and wind generator), conventional backup energy source(diesel engine generator) and energy storage bank (battery bank) to sustainably and efficiently satisfy the energy demand of remote places, especially in developing countries, where main grid electricity has not reached yet due to many geographical and economic constraints. The dynamic model, design and simulation of a Solar-Wind-Battery-DG hybrid power generation system that is connected in a specific combination and with power flow devices or controllers will be proposed here. When the power produced by the wind turbine plus power produced by solar array are more than the demand, the remainder is delivered to the battery and the battery is charged according to the proper charging equation. In contrast, when the power produced by the wind turbine plus that produced by the solar array are less than the demand, battery becomes discharged or diesel generators are employed within the system. Our aim is to minimize the total Net Present Cost and Cost of Energy of the system such that the demand is met and also to find out the emission from the Diesel Generator. MATLAB was used to build the dynamic model and simulate the system and PSO algorithm is used for optimal sizing of system's components. The sizing of the different energy sources when applied to the different power management strategies are also discussed as part of the thesis work.

1.4. Project Description

A proper connection or combination of several renewable energy sources, like Wind Turbines and Solar PV-system along with the energy storage class battery bank, with conventional energy source, like a diesel generator, is completely known as hybrid power system. Hybrid systems can maintain a balanced community-level electricity service, such as rural electrification, offering also the chances to be upgraded or updated through grid connection in the future.

The project which is presented in this paper is to investigate for the best design layout (connection diagram) to size and schedule different system components of the model appropriately; to design the model and simulate for the several power management strategies which are defined for the system of the HPSs, which consists of renewable energy sources (PV-arrays and wind generator), conventional backup energy source (diesel engine generator) and energy storage bank (battery bank) to sustainably and efficiently satisfy the energy demand of remote site. Then, cost analysis will be performed for the different power management strategies so that the most efficient and cost-effective configuration can be selected.

The schematic diagram and description of the project, where energy produced from the different sources reaches the consumption areas after power electronic devices are integrated with the different HPSs to convert one form of power into another, control the overall power flow and enhance the efficiency of the whole system will be discussed in another chapter.

In general, the hybrid system that contains AC diesel generators, an AC and/or DC distribution system, loads, renewable power sources, energy storage, power converters, load management options, or a supervisory control system will be studied, analyzed, designed, modeled and simulated in this thesis project.

1.4. Outline

This thesis paper contains nine chapters. Chapter-1 is about general introduction. Chapter-2 gives us the brief literature review of different papers in which similar kind of works has been performed. Chapter-3 starts with the different soft computing techniques and their importance over hard computing techniques. Chapter-4 describes particle swarm optimization techniques

briefly which have been used for solving the system that will discuss later. Chapter-5 explores about several hybrid components which are used in the system along with their power equation. Chapter-6 explains the procedures how to preliminarily size the system elements, which are incorporated with the selected topology, by taking the load and resources profiles into account. In Chapter-7 the optimized results have been found. Optimized scheduling and sizing results are analyzed to indicate system optimization from environment and economical point of views. Different data tables and graphs are presented in the whole paper. In Chapter-8 the conclusion has been drawn and the future prospect of this work has been discussed also. In Chapter-9 all the reference names from where different data or statement has been taken for the fulfillment of this work, has been shown categorically.

Chapter 2: Hybrid System- Recent Advances

2.1. Introduction

During recent times there have been several studies on off-grid standalone hybrid electricity generation in India and other developing countries. Different types of techniques and approaches have been used related to various scenarios and circumstances, including the evaluation of such as wind turbine, solar photo-voltaic, battery bank, DG's, fuel cells and various hybrid forms of them.

2.2. Reviews on Various RETs

In many developing and developed countries for any kind of electrical application SPV can be frequently used for off-grid standalone power or electricity generation. Moharil and Kulkarni suggested that even though providing access to grid electricity might often be cost-effective because of its low price, using SPV in rural areas also has – unlike grid electricity – advantages on a social, economic and environmental level [5], [6]. More studies on the viability of SPV for remote villages have been conducted by Muneer *et al.* (2005) [7] and Nouni *et al.* (2006) [8].

Chakrabarti and Chakrabarti executed a case study on a remote island of West Bengal; India named "Sagar Deep" [9]. They examined thoroughly different environmental and socio-economic issues and reached on a suitable result that SPV is the one of the best option in cases like this, mostly because of the high costs incurred when transmitting electricity from conventional sources to the extremely remote locations. SPV was proved to be advantageous from a sociological point of view, leading to a significant improvement in commerce, trade and education and more participation of women in community activities. The environmental benefit gained resulted from the fact that externality costs which using fossil fuels would have caused were not incurred with the use of SPV.

Sinha and Kandpal also conducted a study on different small remote villages with low load factors. They found that stand-alone Renewable Energy Technologies (RETs) can be acted as a proper and essential alternative to grid extension [10]. Going through different standalone Solar PV studies and considering the levelized unit cost of electricity (LUCE), it can be found that this technology is generally not a cost-effective alternative to grid extension. Only uses of stand-alone Solar PV can be financially supportive where the grid connection would have to be extended by more than 20 km [9], [11]. Gavanidou and Bakirtzis explored a trade-off between SPV array sizing and number of batteries within a system to maintain the system costs low on the one hand, and for the minimum Loss of Load Probability (LOLP) requirement on the other [12].

Kaldellis proposed a method for the south-east Mediterranean islands to minimize the electricity generation costs and maximize the contribution of SPV to the energy mix with the help of best possible energy storage devices. The results from this study proved existing thermal power stations to be more expensive and unreliable than the SPV model [13]. Solar-Diesel hybrid micro-grids were designed by Schmitt *et al.* [14] in various sizes ranging from 10 to 30 kW. After implementation of these studied systems, about 90% of the villages in developing countries would have been electrified according to their study. Kaushika *et al.* [15] employed interconnected SPV arrays instead of the traditional single aperture model to increase the amount of electricity produced. Furthermore, to arrive at the right system size, they carried out a simulation and introduced the loss of power supply probability (LPSP) to take into account the risk of a failure of power supply by both the PV modules and the batteries. To optimize the number of PV modules and batteries, a linear programming model was employed

Mayer and Heidenreich [16] looked into the reasons for unsatisfactory performance of Solar PV stand-alone systems and found out that it is not happening due to some technical problems of the system, but that several system related errors like a mismatched relation between load factors and generation potential or inappropriate sizing are responsible for the problems. The authors tried to obtain better performance indicators for SPV stand-alone systems by introducing new coefficients, which they held to be superior to current coefficients due to various shortcomings of the latter, which are pointed out in detail.

In the remote regions of Kenya, almost 99.5% of rural households and 80% of the households in cities are not grid-connected. A case study had been formulated by Rabah [17] on this area. He pointed out the use of stand-alone SPV systems to improve this scenario. Bates and Wilshaw have summarized the status of SPV power systems, the government policies concerning it and key market barriers hampering its fast dispersion [18]. The combination of stand-alone SPV with a DG was examined by Kolhe *et al.* [19]. It was observed that SPV were techno-economically more efficient and gave an output of 15kWh/day and 68kWh/day when the economic circumstances were better, making SPV market-competitive.

Dalton *et al.* completed a study by which the load demands of many big enterprises and large hotels can be met by specific standalone renewable energy system. They observed that wind energy is much more cost effective than SPV, because SPV takes too much space for large scale production which is very disadvantageous [20]. Diaf *et al*. also explored a new concept for the uninterrupted power supply of wind energy for a hybrid of SPV and Wind system. This model had technical and economic sub-models based on the levelized cost of energy (LCOE) and optimized to obtain the sizing of the system [21]. Elhadidy and Shaahid [22] examined the possibility of providing electricity to one hundred residential buildings (two bedrooms each) in Saudi Arabia with the help of a wind–diesel hybrid system. They concluded that the pressure on and the usage of the diesel backup system was reduced considerably if the amount of energy storage is increased by increasing the number of batteries.

Mahapatra *et al.* worked on home lighting system or domestic lighting system in different remote regions. They come to the conclusion that the modern concept of the generation by bio-energy system for the whole village and Solar PV for each house could be the suitable and reliable replacement of the traditional kerosene lamps [23]. Ravindranath *et al.* assessed the possibility of carbon reduction in case of Bio Energy Technologies (BETs). They specifically compared BETs with fossil fuel technologies and came to the point that BETs were able to reduce carbon effectively. Seven conventional generation systems were replaced by ten BET projects, and in six projects the cost for carbon reduction diminished [24].

2.3. Reviews on Hybrid Systems

Koutroulis *et al.* [25] worked with genetic algorithms to optimize the sizing of a standalone hybrid system and to minimize the system costs. They found that wind-solar hybrid system is much cost-effective than of these resources individually. When carrying out their analysis, they took into account various technical details of the system such as the PV modules' tilt angle or the installation height of the wind turbines that were significant for either the COE or for the installation and maintenance costs.

A case study on Dahran which had energy demand of 620,000 KWh/year was conducted by Shaadid and Elhadidy. They built a hybrid SPV-DG-battery system, with 175 KW DG and 80KW SPV, which led to a COE of 0.149 $/KWh. The authors envisaged several scenarios in their study and examined the difficulties arising such as unmet load situations, emission decrease, excess electricity and the energy cost [26].

Katti and Khedkar developed a simple numerical algorithm and a weather-based model that was used as a decision support technique to optimize electricity generation of off-grid SPV or wind systems or a hybrid of both [27]. The domestic energy demand of Kanvashram in the Pauri Garhwal district, Uttarakhand was met by a mix of renewable and conventional power sources in a study by Fernandez *et al.* [28].

A combination of SPV and a small wind turbine with fuel cells was used by Agbossou *et al.* The combination with fuel cells for excess electricity was found to be well suited for remote communication applications. The use of PEM fuel cells could stabilize the electricity supply for communication stations in unfavorable weather. The fuel cell system responded to fast load switching and its efficiency of converting hydrogen into electricity was over 42% [29].

Nayar developed the designs of solar-wind hybrid systems to supply electricity to remote areas of Australia. These hybrid RET systems were studied with different configurations of switched, parallel, and series connections [30]. Also the optimal of sizing of a solar-wind hybrid system is the study by Lietzmann *et al.* [31]. They configured a method to determine the exact load demand of the location and to calculate the appropriate size of SPV array with batteries for best results. Santarelli *et al.* studied the integration of RE systems of SPV, wind energy and SHP. They developed a model for a stand-alone system and tried to combine it with a stand-alone

hydrogen based energy system. Their study mainly focused on energy analysis, electricity management and hydrogen management for locations in the mountains of Italy [32].

An integrated RE system model for Jaunpur in Uttarakhand, India was developed by Akella *et al.*, who optimized a system comprising of SHP, wind, biomass and solar energy with the help of the Electric Power Delivery Factor (EPDF). If this factor ranged between 1.0 and 0.75, the RE system could provide a practicable energy solution. Below this range, however, the system would not be viable [33]. Fuel cells were also used by in combination with a SPV – battery system Lagorse *et al.* They used genetic algorithm and simplex algorithm techniques to justify the proposed model for optimized solution [34].

Rana *et al.* tried to match the least costly off-grid electricity generation technologies with the resources available in the villages of Madhya Pradesh, India. This study allowed the classification of villages into five categories according to the energy resources available and the consequently suitable technologies [35]. The Levelized Unit Cost of Electricity (LUCE) for various off-grid power generation technologies in India was analyzed by Banerjee [36]. Similar studies for all kinds of off-grid electricity generation (for example DG systems, SHP projects, SPV systems, small wind turbines and biomass gasifier-based dual-fuel engines) have been carried out, examining their unit capital cost and LUCE. Some of them have been installed in the fields for further studies [8]. Potential areas for off-grid power generation systems in remote areas of India were tagged in Nouni *et al.*'s in-depth study on electricity access [37].

Another paper dealing with electricity access in remote villages was that of Chaurey *et al.,* which evaluated the particular problems of electrifying remote villages and employing off-grid RETs [38]. The factors taken into account in the course of Integrated Renewable Energy Planning (IREP) had been pointed out by Ahmed and Cohen. These were T&D, and supply and demand side [39]. Ramakumar *et al.* used the knowledge-based concept of Loss of Power Supply Probability (LPSP) to keep the capital cost for the use of RE systems in off-grid locations as low as possible [40, 41]. An integrated goal programming (GP) – Analytic Hierarchy Process (AHP) model was applied by Ramanathan and Ganesh to provide domestic lighting. For this study seven different power sources were tapped [42].

Iniyan *et al.* developed a model called Optimum Renewable Energy Model (OREM) to efficiently harness RETs for purposes such as transportation, heating and cooling, pumping, lighting and cooking in India for 2020-2021 [43]. Using a mathematical model with power flow calculations and distribution system models, Ramakumar and Chiradeja found that using a DG transmission losses were reduced as well as system voltage profile was improved [44].

A study on rural Japan was conducted by Nakata *et al.* They supplied heat and electricity from various RES available with the help of hybrid optimization modeling [45]. Ashok tried to find the optimal combination of components for a hybrid power generation system for a typical off-grid location of Western Ghats in Kerala, India. To compute the optimal size of each component with regard to achieving the lowest possible total life cycle cost (LCC), he employed a Quasi-Newton algorithm that is non-linear constrained optimization techniques [46].

Using Linear Programming, Ramakumar *et al.* identified the different resources required to determine the optimal size for an integrated RET system's components. Their aim was to reduce the total annual cost of power generation. In other studies, the same author designed and analysed IRES with a knowledge-based tool, expressing the systems' reliability with the help of the loss of power supply probability [40, 47].

Walker laid out the advantages and disadvantages of supplying electricity for low-income households with the help of stand-alone systems and pointed out that only with the help of stand-alone power generation, the goal of carbon zero homes could be reached [48].

Holland *et al.* [49] have dealt with the non-technical issues of stand-alone systems in remote areas and made some suggestions regarding local ownership and participation, market factors, institutional support and other energy management aspects to facilitate the successful dispersion of this system.

2.4. Reviews Related to Studies with HOMER

A definite hybrid Renewable Energy Technology model comprises of Solar PV, Diesel Generator and batteries had been formulated by Karakoulidis *et al.* which could meet the load demand of an electric machinery laboratory in Kavala, Greece. The software HOMER was used here for the optimization and simulation of different combinations and the finally based on the

Net Present Cost (NPC), the best suited configuration was selected [50]. Giatrakos *et al.* created a sustainable RE based system comprising wind energy, SPV and a hydrogen system to replace the existing DG's in the Greek island Karpathos. They used HOMER for system design and planning analysis. With the help of historic data available for both supply and demand, they concluded that a RET system could penetrate up to 20% in electric energy mix [51].

Khan and Iqbal also propounded a pre feasibility study of a hybrid system with hydrogen as energy carrier in Newfoundland, Canada. To overcome the various disadvantages of a stand-alone system (for example high battery costs, limited storage and low capacity) the energy carrier incorporation had been done. Several renewable and non-renewable carriers were discussed, comparing their environmental friendliness and cost-efficiency. In the end, they found a combination of wind turbines, a DG and batteries to be the most efficient solution at the given cost [52]. Barsoum and Vacent also used HOMER for the analysis of a hybrid system and identified the compressed gas method as the most cost-efficient method of hydrogen storage [53].

Türkay and Telli surveyed a remote region to study the adaptability of utilizing solar and wind energy with hydrogen as a storage unit to meet electricity requirements together with a grid connection. HOMER was used for the optimization of the system's technical and economic parameters [54]. Nema *et al.* worked with an optimized model which is a combination of solar PV and wind turbine to replace the DG used at the mobile telephony base station in Bhopal, India. The software HOMER was used to optimize and calculate the load pattern of the system [55].

Givler and Lilienthal conducted a case study in Sri Lanka. They compared stand-alone SPV for small solar homes with an expensive grid connection and used HOMER to optimize the most cost-effective configuration of load size, where using a DG would be cheaper than a battery bank. The results from HOMER's sensitivity analysis showed that a load size of 3-13kWh per day would be cheaper for such a configuration [56].

Munuswamy *et al.* compared the COE from fuel cell based RETs generation to a grid connection for a rural health centre in India, applying HOMER for the simulation analysis. The results showed the EDL to be within a range of 43.8 km to a negative distance (depending on the input

parameters) [57]. Ajao *et al*. conducted a cost-effectiveness analysis to compare a hybrid of wind energy and SPV to the cost per kWh of electricity from the central grid in Nigeria. They employed HOMER and found the system's payback period to be 30 years. They also found electricity from the central grid to be the cheapest, but a grid extension was not possible in most rural areas [58].

2.5. Reviews on Related Areas

Various kinds of activities regarding the reduction of Green House Gas (GHG) emission in the atmosphere in developed or developing countries can be analyzed by Climate change mitigation analysis. Two renowned authors Ravindranath and Sathaye wrote a book named "Climate Change and Developing Countries" where it can be found how the energy sector can contribute to this goal, especially by fuel substitution and the use of energy-efficient technologies [59]. The variation of choosing different kinds of energy technology selected for the generation of electricity is very important as the climate change mitigation area is fully dependent on it which is also the main objective. The pivotal role of grid-connected and stand-alone systems in climate change mitigation has been explored.

Kishore *et al.* discusses about the fact how biomass can contribute in the matter of Green House Gas reduction. They stretch out their study on the procedure by which biomass technology can be commercialized, diffused and gained wide acceptance within the frame of clean development mechanism (CDM) and stress the technology's important role for a village's infrastructure and power supply. Under CDM projects there are many grid connected systems that do not supply electricity to villages or even village clusters; in contrast to this, stand-alone systems can be used to meet the power demand of a particular village and furthermore fulfill the core idea of clean development mechanism [60].

Parmal Singh Solanki and Venkateswara Sarma Mallela conducted a case study in the residential sector in Oman. They showed how the percentage emission of carbon-dioxide is decreased in case of Solar PV-DG hybrid system compared to the only DG system [61].

It must be noted that above research works concentrated on electrifying rural areas in general, without taking the individual villages or clusters of villages into account. Thus, not enough research work is available on supply demand models. Secondly, most studies concentrate on

supplying electricity merely for domestic purposes and the electricity needed for agricultural, irrigation, community purposes and for small-scale business units for the socio-economic development of the whole region has not been emphasized. These conclusions also work as the backbone of the current thesis work.

Chapter 3: Soft Computing Technique

3.1. What Is Soft Computing?

Soft computing technique includes several artificial intelligence techniques where the human mind is used as a model. It works synergistically and aims to exploit the tolerance for imprecision, uncertainty, approximation, and partial truth to achieve tractability, robustness, and low solution cost. These are the guiding principles of this technique. The basic ideas underlying soft computing in its current scenario have links to many earlier influences. Among them Zadeh's 1965 paper on fuzzy sets, the 1973 paper on the analysis of complex systems and decision processes, and the 1979 report (1981 paper) on possibility theory and soft data analysis are main [62]. The inclusion of genetic computing and neural computing in soft computing came at a later point. Soft computing provides intelligent processing techniques which overcome the problem of time consuming and complexity for the hard computing techniques.

The applications of the soft computing techniques are extensively taking place at the data mining step in the Knowledge Discovery in Databases (KDD) process as shown in Figure :-

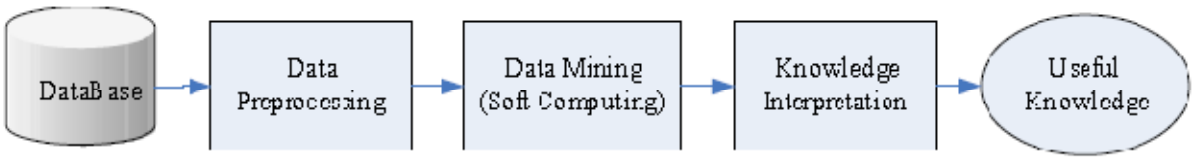

Fig. 3-1: Flow chart showing the Knowledge Discovery in Databases (KDD) process

At this juncture, the principal constituents of Soft Computing (SC) are Fuzzy Logic (FL), Neural Computing (NC), Evolutionary Computation (EC), Machine Learning (ML) and Probabilistic Reasoning (PR) with the latter subsuming belief networks, chaos theory and parts of learning

theory. What is important to note is that soft computing is not a mixture. It is a partnership in which each of the partners contributes a distinct methodology for addressing problems in its domain. In this perspective, the principal constituent methodologies in soft computing are complementary rather than competitive. Furthermore, soft computing may be viewed as a foundation component for the emerging field of conceptual intelligence.

3.2. Importance of Soft Computing

Soft Computing Techniques (Artificial Neural Networks, Genetic Algorithms, Fuzzy Logic Models, and Particle Swarm Techniques) have been recognized as attractive alternatives to the standard, well established “hard computing” paradigms. Traditional hard computing methods always require a precisely stated analytical model and often a lot of computational time. Soft computing techniques, which emphasize gains in understanding different types of system behavior in exchange for unnecessary precision, have proved to be important practical tools for many contemporary problems. Neural networks and Fuzzy logic models are universal approximates of any multivariate function because they can be used effectively for modeling highly nonlinear, unknown, or partially known complex systems, plants, or processes.

Genetic Algorithm and Particle Swarm Optimization Techniques are also very much popular and essential techniques that have emerged as potential and robust optimization tools in recent years.

In various context a problem can be solved most effectively by using FL, NC, GC and PR in combination rather than exclusively. A major example of a particularly effective combination is, now a day’s what has come to be known as "neuro-fuzzy systems." Less visible but perhaps even more effective are neuro-fuzzy systems in industrial applications. The most significant part is that in both consumer products and industrial systems, the employment of soft computing techniques leads to systems which have high MIQ (Machine Intelligence Quotient). In larger periphery, it is the high MIQ of SC-based systems that accounts for the rapid growth in the number and variety of applications of soft computing. One of the important features of soft computing is assimilation or acquisition of knowledge/ information from inaccurate and uncertain data. It is expected that combination or fusion of the elemental technologies will help to overcome the limitations of individual elements.

Soft computing is often robust under noisy input environment and has high tolerance for imprecision in the date on which it operates.

3.3. A Glimpse into the Future

In different sphere the successful applications of soft computing and its rapid growth suggest that the impact of soft computing will be felt increasingly in upcoming years. Soft computing is likely to play an especially huge role in science and engineering sector, but practically its influence may extend much further.

3.4. Different Evolutionary Algorithms

This section gives the brief descriptions of various kinds of evolutionary algorithms or computation techniques. They are as follows:-

3.4.1. Genetic Algorithm (GA)

During the last few decades, GA has been considered as one of the most important and powerful computational technique which can solve various optimization problems. It consists of four steps i.e. representation, initialization, selection and reproduction with crossover and mutation. With respect to the type of representation genetic algorithm can be broadly classified into two groups:-

(1) Binary coded genetic algorithm (BCGA) and

(2) Real coded genetic algorithm (RCGA).

3.4.1.1. Binary Coded Genetic Algorithm (BCGA):

In BCGA, all the real world problems (phenotype space) are encoded to binary representation (genotype). Each element of a solution vector is represented by a binary string $zi[zi \in [x, y]] = [ai^1, ai^2, \ldots, ai] \in [0, 1]$. The length of the binary string (chromosome) L depends on how much accuracy is required.

For BCGA, there are several selection methods to form the parent pool such as proportionate reproduction, tournament selection, rank selection, genitor selection, etc. In this paper, binary tournament selection scheme is used because of its less time complexity [63].

Crossover is a kind of a method for sharing information between chromosomes. It combines the features of parent chromosomes to form offspring. Commonly used crossover techniques are one point crossover, two point crossovers, *n* point crossover, uniform crossover, heuristic crossover, etc. Crossover operation makes a big jump to an area somewhere in between the two parents (explorative) whereas mutation creates random small diversions near the parent (exploitative). Typically mutation probability is very low (of the order of .01).

3.4.1.2. Real Coded Genetic Algorithm (RCGA):

BCGA has some problems of binary representation when dealing with continuous search space with large dimensions and improved numerical precision. RCGA does not have any such difficulties [64]-[65]. In RCGA genes are represented directly as real numbers and a chromosome is a vector of floating point numbers. As RCGA deals directly with real numbers, there is no need of phenotype to genotype conversion and vice versa. Any decision vector x is represented as follows: $x = [x1, x2, \ldots, xn]$, where n is the number of parameters to be optimized.

There are different types of crossover techniques for RCGA such as flat, simple, arithmetic, blend, linear, discrete, logical FCB (connectives Based Crossover) etc. Among different crossover techniques blend (with α =.5), linear and logical FCB crossover techniques outperform the others [66].

There are different types of mutation techniques for RCGA such as non-uniform, real number creep, continuous modal mutation, discrete modal mutation. Among them non-uniform crossover is very effective for RCGA [66].

3.4.2. Particle Swarm Optimization (PSO)

In 1995, Kennedy and Eberhart first introduced the PSO method motivated by social behavior of organisms such as fish schooling and bird flocking. It is also a population based search technique. As I have used this optimization technique in my present work so it has been described in brief in the next chapter.

3.4.3. Bacteria Foraging Optimization (BFO)

BFO method was invented by Kevin M. Passino [67] motivated by the natural selection which tends to eliminates the animals with poor foraging strategies and favor those having successful foraging strategies. The foraging strategy is governed by four processes namely Chemo taxis, Swarming, Reproduction, and Elimination & Dispersal.

Chemotaxis

Chemotaxis process is the characteristics of movement of bacteria in search of food and consists of two processes namely swimming and tumbling. A bacterium is said to be swimming if it moves in a predefined direction, and tumbling if it starts moving in an altogether different direction. Let, j is the index of chemotactic step, k is the reproduction step and l is the elimination dispersal event. Let, θ□ (j, k, l) is the position of i-th bacteria at j-th chemotactic step, k-th reproduction step and l-th elimination dispersal event. The position of the bacteria in the next chemotactic step after a tumble is given by:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + C(i)\,\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \qquad (3.1)$$

Where

C (i) step size;

Δ (i) random vector;

$\Delta^T(i)$ transpose of vector Δ (i).

If the health of the bacteria improves after the tumble, the bacteria will continue to swim to the same direction for the specified steps or until the health degrades.

Swarming

Bacteria exhibits swarm behavior i.e. healthy bacteria try to attract other bacterium so that together they reach the desired location (solution point) more rapidly. The effect of Swarming is to make the bacteria congregate into groups and move as concentric patterns with high bacterial density. Mathematically swarming behavior can be modeled:

$$J_{cc}(\theta, P(j,k,l))$$

$$= \sum_{i=1}^{S} J_{cc}^{i}(\theta, \theta_i(j,k,l))$$

$$= \sum_{i=1}^{S} [-d_{attract}\, exp(-w_{attract}) \sum_{m=1}^{P} (\theta^m - \theta_i^m)^2]$$

$$+ \sum_{i=1}^{S} [-h_{replent}\, exp(-w_{replent}) \sum_{m=1}^{P} (\theta^m - \theta_i^m)^2] \quad (3.2)$$

Where

Jcc : the relative distances of each bacterium from the fittest bacterium.

S : number of bacteria.

p : number of parameters to be optimized.

θ^m : position of the fittest bacteria.

$d_{attract}$, $w_{attract}$: different parameters.

$h_{replent}$, $w_{replent}$:different parameters.

Reproduction

In this step, the population members who have had sufficient amount of nutrients will reproduce and the least number of healthy bacteria will die. The healthier population replaces unhealthy bacteria which get eliminated owing to their poorer foraging abilities. This makes the population of bacteria constant in the evolution process.

Elimination and Dispersal

In this evolution process a sudden unforeseen event may drastically alter the evolution and may cause the elimination and/or dispersion to a new environment. Elimination and dispersal helps in reducing the behavior of stagnation i.e. being trapped in a premature solution point or local optima.

3.4.4. Ant Colony Optimization (ACO)

Ant Colony Optimization was first invented by Marco Dorigo and colleages [68]-[69] inspired by the foraging behavior of ant colony. At the time of movement from one place to another, each ant lays certain amount of pheromone on the path. Ant's use the pheromone trails to communicate information among the individuals and based on that each ant decides the shortest path to follow.

ACO technique has been successfully implemented for several difficult discrete combinational optimization problems such as Traveling Salesman Problem [70], Sequential Ordering [71], Routing in communication problems [72], etc. In recent few years a large number of literatures have been published [73]-[75] where ACO algorithm has been successfully used for continuous optimization problems. The algorithm can be distinguished in four stages: Solution construction, Pheromone update, Local Search and Pheromone Re-initialization.

Solution Construction

In this method, initial position of each ant i.e. initial solution vectors are generated randomly in the feasible search region. In each iteration, artificial ant constructs the solution by generating a random number for each variable using the normal distribution $N\ (\mu_i,\sigma_i^2)$. Mean (μ_i) and standard deviation (σ_i^2) for each variable i changes with iteration number based on the experience of the colony.

This is synonymous to pheromone update in basic ant colony optimization.

Let $x = [x_1,\ldots,x_n]$ is a solution constructed by any ant using normal distribution $N\ (\mu_i,\sigma_i^2), i \in \{1,\ldots,n\}$ associated with each variable x_i. Here n is the number of parameters to be optimized. After construction of each solution, upper and lower bound for each parameter is checked and the solution is modified if it goes out of search space:

$$x_i = \begin{cases} a_i & \underset{x_i<a_i}{} \\ x_i & a_i \le x_i \le b_i \\ b_i & \underset{x_i>b_i}{} \end{cases} \tag{3.3}$$

Where, b_i and a_i are upper and lower bound of variable x_i respectively.

Pheromone update

Pheromone update procedure composed of pheromone evaporation and pheromone intensification. Pheromone initialization is done as follows:

$$\mu\,(0) \;=\; a \;+\; rand\,(i)\;(b \;-\; a) \tag{3.4}$$

$$\sigma\,(0) \;=\; (b \;-\; a)\;/\;2 \tag{3.5}$$

After construction of solutions, pheromone evaporation phase is performed as follows:

$$\mu\,(t) \;=\; (1 -\; \rho_1)\,\mu\,(t \;-\; 1) \tag{3.6}$$

$$\sigma\,(t) \;=\; (1 -\; \rho_1)\,\sigma\,(t \;-\; 1 \tag{3.7}$$

where, t is iteration number and $\rho_1 \in [0,\ 1]$ is the evaporation parameter, a uniform random number between 0 and 1.

The aim of pheromone intensification is to increase the pheromone value associated with promising solutions. This is done as follows:

$$\mu\,(t) \;=\; \mu\,(t) \;+\; \rho_2 x^{gb} \tag{3.8}$$

$$\sigma\,(t) \;=\; \sigma\,(t) \;+\; \rho_2 |x^{gb} \;-\; \mu\,(t \;-\; 1)| \tag{3.9}$$

Where, $\rho_2 \in [0, 1]$ is the intensification parameter, a uniform random number between 0 and 1 and x^{gb} is the global best solution found in last (t-1) iteration.

Local Search

Local search in the vicinity of current solution may improve the solution constructed. Local search is usually made before updating the pheromone.

Chapter4: Particle Swarm Optimization

4.1. Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is a population-based heuristic algorithm for numerical optimization. In 1995, Kennedy and Eberhart first introduced the PSO method motivated by social behavior of organisms such as fish schooling and bird flocking. It uses a population of search points, new potential solutions are stochastically generated based on the information drawn from the best ones, and it requires only function values disregarding the existence of gradient information. These properties allow PSO to efficiently work on problems where only limited information on the objective function is available or accessible. Paradigms can also be implemented in a few lines of computer coding. So, it takes very less amount of computer memory. It takes very much less time to converge due to the requirement of primitive mathematical operators [76].

PSO is an iterative search technique in which particle moves around the wide area of search space according to objective function (OF). Movement of each particles are based on its own experience as well as others experience.

There is an interesting concept of the birds flocking or fish schooling technique arrives by which the theory of PSO can be understood. The technique is based upon the food searching criterion. Let in the following scenario, a bird flocks or a group of fishes are searching a wide area randomly. There is only one piece of food in the area being searched. All the birds/fishes do not know the exact location of the food. In that consequence, they travel in search space according to the own experience as well as neighbour experience. That mean, in each iterations they compare the distance between its own location and the target with respect to its previous experience as well as the best position of neighbour which is closest to the target. After that they modify its own speed for the best strategy to find the food. This is the basic principle of Particle Swarm

Optimization (PSO) algorithm. In technical term, each birds or fishes are called “Particles” and its flock is called “Particles Population”. All the particles have own fitness or objective value which is calculated by the Objective Function (OF). For the optimization of OF, particles positions are updated by its velocity vector which depends on its personal influence as well as social influence.

In the PSO, first of all we randomly initialize the particles position according to problem constraints. The set of all particles position is called initial population or initial swarm. After that we generate random velocities for each particle. According to the objective function, cost of the system or objective value is evaluated. In the initial condition, position corresponds to optimum cost is called personal best or “pbest” (pb) as well as global best (gb) or “gbest” (only for initial condition). Update the particles’ velocities (v_i) and positions (x_i) according to personal influence and social influence. In the mathematical form, velocity updates according to expression:

$$v_i^{t+1} = v_i^t + c_1 U_1^t (pb_i^t - x_i^t) + c_2 U_2^t (gb^t - x_i^t) \quad (4.1)$$

And position updates according to expression:

$$x_i^{t+1} = x_i^t + v_i^{t+1} \quad (4.2)$$

Where, c_1 is called ***cognitive parameter***

c_2 is called ***social parameter*** } Both are called ***acceleration coefficients.***

U_1^t & U_2^t are two ***random numbers*** varies between 0 to 1.

In the next iteration, updated velocities and positions are used as the present velocities and positions. Now these particle positions are used for the calculation of new cost. In that condition, position of particle corresponds to optimum of all costs is called new “gbest” and position of particle corresponds to optimum of cost that was evaluated by itself, is called new “pbest”. And these above processes are repeated until stopping criteria (limitation of maximum iteration) is satisfied.

4.2. Algorithm

1. Start.
2. Create a population of agents (called Particle) uniformly distributed over search space ($\mathcal{X}$).
3. Evaluate each particle's position according to the objective function.
4. If a particle's current position is better than its previous best position, update it.
5. Determine the best particle (According to the particles previous best position).
6. Update particles velocities according to the equation (4.1).
7. Move particles to their new positions according to equation (4.2).
8. Go to step 2 until stopping criteria are satisfied.
9. Stop.

The pseudo code of the procedure is as follows:

Initialize the population size.

For each particle in the population

    Initialize particle randomly according to problem's condition.

End

Do

For each particle

    Calculate fitness value or cost

    If the fitness value is better than the best fitness value (pbest) in history

        Set current value as the new pbest

    End

End

Choose the particle with the best fitness value in the population/swarm as the gbest.

For each particle

Calculate particle velocity according to equation.

Update particle position according to equation.

End

While maximum iterations or minimum error criteria is not attained.

4.3. Flow Chart

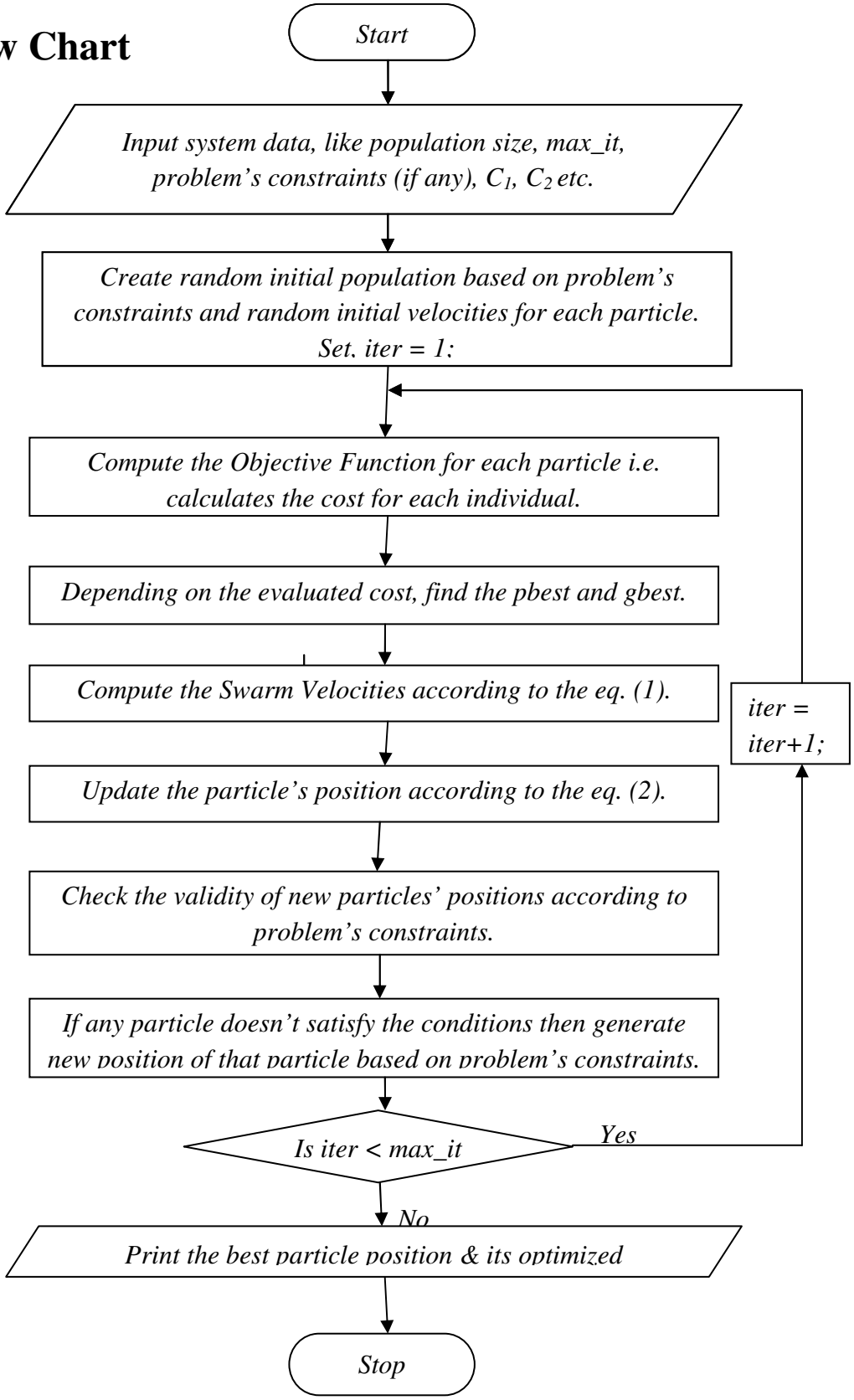

Fig. 4-1: Basic PSO algorithm.

4.4. Different types of PSO

Basic PSO may not suitable for all type of problems. For the application of PSO in the different types of problems, many variants of the original algorithm have been proposed. Depending on the variations in the constants or solution technique, there are different types of PSO have been proposed.

4.4.1. Canonical Particle Swarm Optimization

Maurice Clerc and James Kennedy [84] included a new kind of technique into the Particle Swarm Optimization in 2002. Combination of several parameters determines the convergence properties of the algorithm. To control the convergence properties of the particles they introduced a "*Constriction Factor (X)"* into the basic PSO. After introducing the Constriction Factor (X), the velocities update formula becomes:

$$v_i^{t+1} = X\,(v_i^t + c_1 U_1^t\,(pb_i^t - x_i^t) + c_2 U_2^t\,(gb^t - x_i^t)) \qquad (4.3)$$

Where,

$$X = {2k}\Big/{(\left|2 - \varphi - \sqrt{(\varphi^2 - 4\varphi)}\right|)}$$

Here c_1 is the "cognitive parameter" and c_2 is the "social parameter", k is a random number which varies from 0 to 1, i.e. $k \in [0,1]$, $\varphi = c_1 + c_2$ and φ should be greater than 4. Generally, k is set to *1* and both $c_1 \& c_2$ are set to *2.05*, giving as a result *X* equal to *0.729*.

4.4.2. Time Varying Inertia Weight Particle Swarm Optimization (TVIW-PSO)

Yuhui Shi and Russell Eberhart [85] proposed a technique into PSO in 1998. They introduced a *"time varying inertia weight, w (t)"* into the basic PSO to control the diversification-intensification behavior of the original PSO. The velocity update rule becomes:

$$v_i^{t+1} = w(t).v_i^t + c_1 U_1^t (pb_i^t - x_i^t) + c_2 U_2^t (gb^t - x_i^t) \quad (4.4)$$

Generally *time varying inertia weight, w (t)* always varies linearly from an initial value to final value. In most cases, both the parameters $c_1 \& c_2$ are set to *2* [84].

There are two ways of varying the inertia weight in time. Time varying inertia weight means the value of inertia weight changes from one iteration to other iteration. If its values continuously decreases then this is called "*Dec-IW*" and it was proposed by Yuhui Shi and Russell Eberhart [85]. If the value of *w(t)* continuously increases then this is called "*Inc-IW*" and it was proposed by Zheng et al. [86]. Normally, the starting value of the inertia weight is set to 0.9 and the final to 0.4 for *Dec-IW* and from 0.4 to 0.9 for *Inc-IW.* Sometimes both variants are included for the sake of completeness.

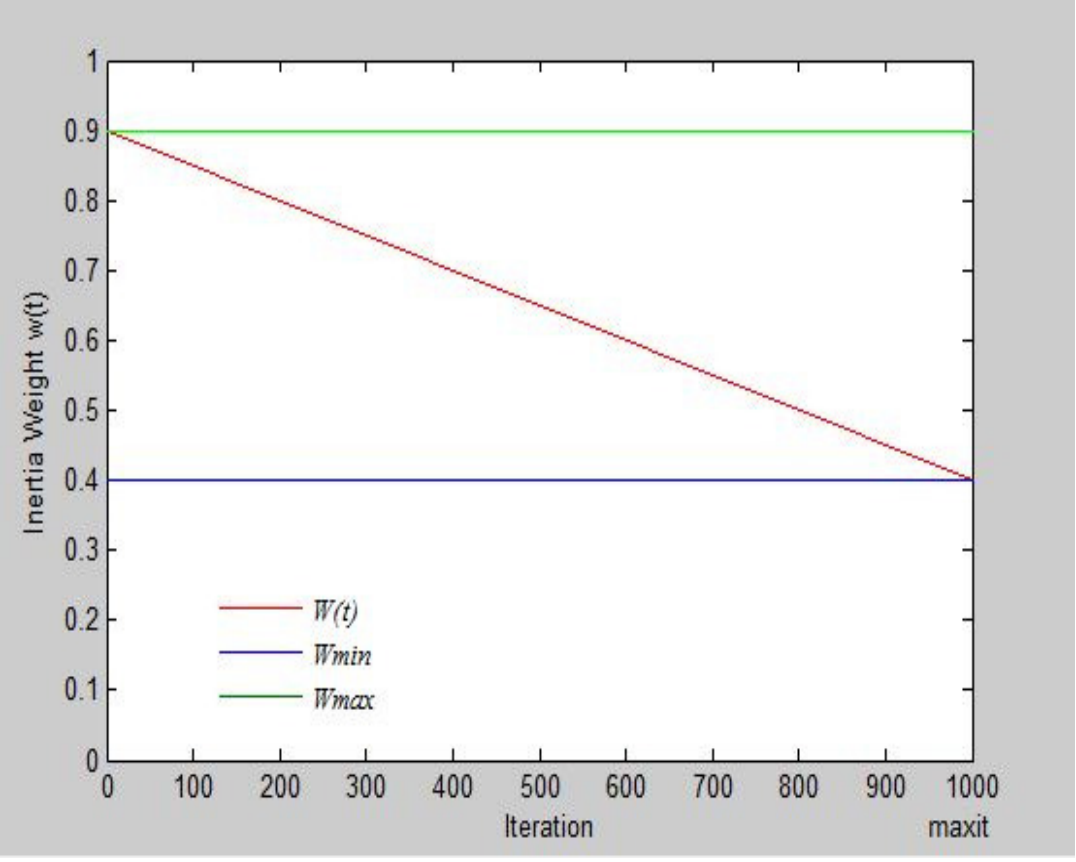

Fig. 4-2: Inertia Weight versus Iteration

Mathematically it can be written as:

For *Dec-IW,*

$$w(it) = w_{max} - \frac{w_{max} - w_{min}}{it_{max}} . it \quad (4.5)$$

For *Inc-IW,*

$$w(it) = w_{min} + \frac{w_{max} - w_{min}}{it_{max}} . it \quad (4.6)$$

Where,

$w(it)$ ⇒ Inertia weight varies with respect to iteration number

w_{max} ⇒ Maximum value of inertia weight i.e. 0.9

w_{min} ⇒ Minimum value of inertia weight i.e. 0.4

it ⇒ Iteration number

it_{max} ⇒ Maximum number of iteration

4.4.3. Stochastic Inertia Weight Particle Swarm Optimization (Sto-IW PSO)

Russell Eberhart and Yuhui Shi proposed another variant into PSO. This technique was first introduced by them. In this technique according to a uniform distribution in the range [0.5, 1.0] the *inertia weight* is randomly selected. This range was inspired by *Maurice Clerc and James Kennedy's* constriction factor. In this version, both acceleration coefficients c_1 and c_2 are set to 1.494 [84]. Although this variant was originally proposed for dynamic environments, it has also been shown to be a competitive optimizer for static ones. In Stochastic variant a new update rule and re-produce strategy has been evolved, and it can convergent onto global optima with probability one. However, due to the large global search capability, the exploitation capability is not well.

4.4.4. Fully Informed Particle Swarm Optimization (FI-PSO)

Mendes et al. [83] introduced this technique first. In the basic PSO, particle influences only from best particle. But in this version, particle uses information from all its topological neighbors. This variant is based on the fact that Clerc and Kennedy's constriction factor does not enforce that the value ' should be split only between two attractors. For taking information from all neighbors, φ $(where, \varphi = c_1 + c_2)$ is decomposed in $\varphi_k = \varphi/|N|,\ \forall\ k \in N$, where N is the neighborhood of the particle. If we consider this terminology then the new velocity update equation becomes

$$v_i^{t+1} = X\ [v_i^t + \sum_{k \in N}\ \varphi_k\, w(k) U_k\ (p_k - x_i^t)] \tag{4.7}$$

Where $w(k)$ is a weighting function.

4.4.5. Time-Varying Acceleration Coefficients Particle Swarm Optimization (TVAC-PSO)

In the standard PSO method information of each particle in the swarm are recorded by different variables. They are guided by personal influence as well as social influence which depend on cognitive parameter (c_1) and social parameter (c_2) respectively. These two parameters are called acceleration coefficients. Therefore, proper control of these two components is very important to find the optimum solution accurately and efficiently. In this technique, we vary the acceleration coefficients (cognitive and social parameter) with respect to time or iteration. At the beginning, we select large cognitive component and small social component. And in the latter stage, we select small cognitive component and large social component. Variation is added only in the terminal iterations to prevent premature convergence. Due to this type of selection, particles are allowed to move around the search space, instead of moving toward the population best at the beginning and on the other hand, particles try to converge to the global optima in the latter part of the optimization. TVLPSO has good potential in finding better solutions.

Mathematically these variations can be represented as

$$c_1 = c_{1i} + \frac{c_{1f} - c_{1i}}{it_{max}}.it \tag{4.8}$$

$$c_2 = c_{2i} + \frac{c_{2f} - c_{2i}}{it_{max}}.it \tag{4.9}$$

It was observed that when c_1 varies from 2.5 to 0.5 and c_2 varies from 0.5 to 2.5 gives better result, i.e. we should take c_{1i} = 2.5, c_{1f} = 0.5, c_{2i} = 0.5 and c_{1f} = 2.5 for better results.

4.4.6. Self-Organizing Hierarchical PSO with Time-varying Acceleration Coefficients (HPSO-TVAC)

This technique was first introduced by Ratnaweera et al. [82]. He drops the velocity term from the right side of the equation that is described on time varying inertia weight context. In this technique, they proposed the new velocity update formula as:

$$v_i^{t+1} = c_1 U_1^t (pb_i^t - x_i^t) + c_2 U_2^t (gb^t - x_i^t) \tag{4.10}$$

But the variation in the acceleration coefficients is similar to TVAC-PSO i.e. c_1 varies from 2.5 to 0.5 and c_2 varies from 0.5 to 2.5 according to equations. During the velocity calculation, if a particle's new velocity becomes zero (in any dimension), then in that condition, that velocity is reinitialized to some value according to the maximum allowable velocity *Vmax*. Finally, the re-initialization of velocity is also linearly decreased from *Vmax* at the beginning of the run to (0.1**Vmax*) at the end. From the above discussion an overview about the optimization technique of PSO can be found. In the proposed hybrid system that will be discussed from the next chapter, a type of PSO named Stochastic Inertia Weight PSO method has been used for the optimization.

Chapter 5: Hybrid System Components

5.1. Components of the Hybrid Energy System

The hybrid energy system comprises of various renewable and non-renewable energy sources. Renewable sources may be solar PV, wind turbine and biomass and sometimes battery or some other conventional sources like diesel generator can be incorporated into the system which can serve as the back-up power at the time of energy deficit. For the present thesis work, a test system comprising PV/Wind/Battery/Diesel energy system has been considered. Output of the solar PV and wind are not reliable as the solar irradiance and wind speed is intermittent in nature. Therefore, battery is used as a storage device that can deliver power at the time of shortage in energy output. When the battery also is unable to meet the demand power then the conventional diesel generator comes into the picture. A strategic optimization has been done for the operation between battery and diesel generator. In the following section, the different components of this proposed hybrid system will be discussed briefly.

5.2. Solar Energy

Solar energy is of intermittent nature and mainly depends on the solar irradiance and different other parameters. There are different kinds of solar radiation and different terminology relating to solar angles. Measurement of different solar radiation and the angles are required to calculate the total solar radiation on which the output of the solar PV depends. In the following section, a different type of solar radiations that comes from the solar energy has been discussed. Later there will be a description of the solar angles also. In the next chapter it has been seen how this several solar radiations and solar angles are responsible for the calculation of total global solar radiation as well as the output power from the solar PV array.

Extra Terrestrial Solar Radiation

Solar radiation continuously strikes the earth's outer atmosphere at the rate of 1.7 x 1017 watts [101]. This is referred to as extraterrestrial radiation. Expressed on a per unit area basis, the yearly average rate of solar radiation striking a surface normal to the rays of the sun outside the earth's atmosphere is called the solar constant, which will be discussed later. The distance between the earth and the sun varies a little through the year. Because of this variation, extra-terrestrial (outside the earth's atmosphere) flux also varies. The earth is closest to the sun in the summer and farthest away in the winter. Earth's orbit is not a perfect circle. It is elliptical, or slightly oval-shaped. This means there is one point in the orbit where Earth is closest to the Sun, and another where Earth is farthest from the Sun. An estimate of the actual extraterrestrial solar flux (flux = flow rate per unit area per unit time), I_o, on any day of the year can be calculated from the following equation:

Approximately [102],

$$I_0 = I_{SC}\left[1 + 0.034\cos\left(\frac{360n}{365}\right)\right](W/m^2) \quad (5.1)$$

Where,

I_0 - Extra-terrestrial radiation.

n – Day of the year.

Terrestrial Radiation

Terrestrial solar radiation is that which reaches the earth's surface. From the utilization point of view solar radiations received at the earth's surface are to be considered and it is quite different from extra-terrestrial radiation, for reasons of scattering, absorption etc. in the earth's atmosphere. It can be broke down into two components beam radiation (also called direct radiation or direct beam radiation) and diffuse radiation. The components are described next.

Beam Radiation

Beam radiation is solar radiation that passes through the atmosphere in essentially a straight line without being reflected, scattered or absorbed by particles or gases in the air. Solar flux (energy rate/unit area) incident on a surface without significant direction or scattering in the atmosphere is called beam radiation. Beam radiation is also called direct radiation. Solar collectors that focus sunlight usually operate on just the beam portion of the incoming radiation since those rays are the only ones that arrive from a consistent direction. Most photovoltaic systems, however, don't use focusing devices, so all three components—beam, diffuse, and reflected—can contribute to energy collected. Beam radiation also helps to calculate the anisotropy index at the time of solar radiation as well as solar PV output power calculation.

Diffuse Radiation

Diffuse radiation is solar radiation, which is scattered, reflected or absorbed by molecules of air, water vapor, aerosols and dust particles, but ultimately still reaches the earth's surface. The diffuse component of solar radiation striking a solar collector also includes solar radiation reflected from the adjacent earth's surface. Solar flux dispersed by various scattering mechanisms into the sky dome without a specific incidence angle on a terrestrial surface. The diffuse radiation on a collector is much more difficult to estimate accurately than it is for the beam. Because, there are variety of components that make up diffuse radiation. Incoming radiation can be scattered from atmospheric particles and moisture, and it can be reflected by clouds. Some is reflected from the surface back into the sky and scattered again back to the ground. At the time of solar radiation as well as solar PV output power calculation with the help of diffuse radiation, the diffuse fraction and the beam radiation can be calculated.

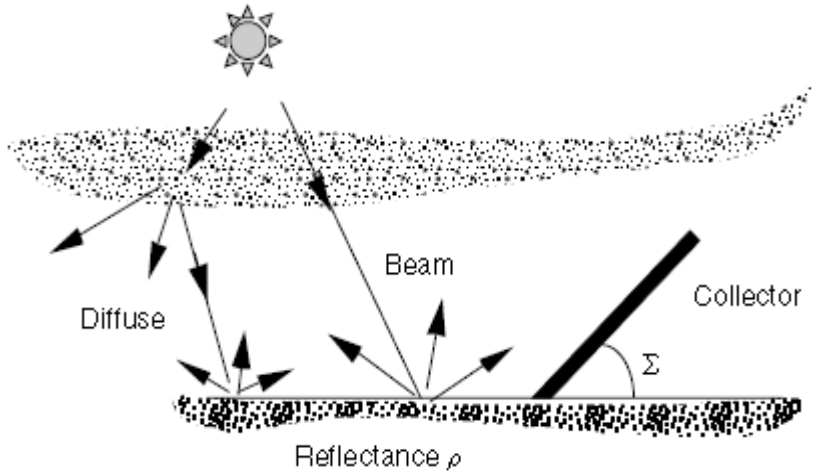

Fig.5-2: The ground is assumed to reflect radiation with equal intensity in all direction [88]

Solar Constant

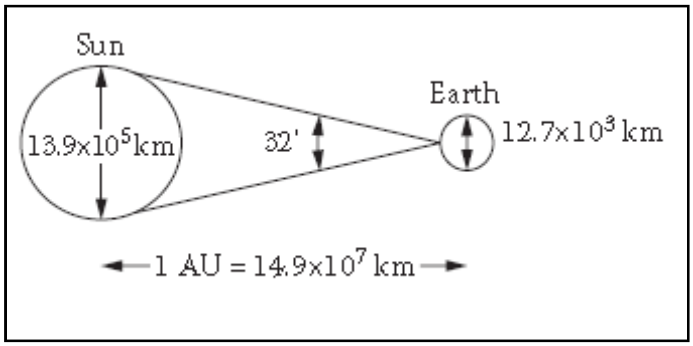

Fig. 5-1: Earth–Sun geometric relationships

The rate at which solar energy arrives at the top of the atmosphere is called solar constant (I_{SC}). This is the amount of energy received in unit time on a unit area perpendicular to the sun's direction at the mean distance of the earth from the sun It has a NASA (give full form) standard value of 1.353 KW/m² or 1353 W/ m² or 1.940 cal/cm² or 1165 Kcal/hm² or 4871 KJ/m²h or 428 BTU/hft² [87].

Air Mass (m)

The air mass m is the ratio of the path of the sun's rays through the atmosphere to the length of path when the sun is at the zenith (directly overhead) at sea level.

m = 1, (when sun is at zenith);

m = 2, (when zenith angle is 60°);

m = $\sec \theta_Z$, (when m>3);

m = 0, (just above the earth's atmosphere);

The air mass coefficient can be used to characterize the solar spectrum after solar radiation has traveled through the atmosphere. The air mass coefficient is commonly used to characterize the performance of solar cells under standardized conditions, and is often referred to using the syntax "AM" followed by a number. "AM 1.5" is almost universal when characterizing terrestrial power-generating panels.

Solar Angles

There are several angles that can be obtained from sun earth geometry. The angles are also responsible for the solar radiation that falls on the earth surface. These angles can be classified in the following manner.

1. Latitude (Φ)

It is the angle made by the radial line joining the location to the centre of the earth with the projection of the line on the equatorial plane. By convention, latitude is measured positive for the northern hemisphere. The latitude of the site is an important parameter because of the effect of latitude on the altitude angle of the sun. The effect of latitude is illustrated by the fact that as one goes north from the equator; the sun is lower in the sky in the winter.

2. Declination Angle (δ)

It is the angle made by the line joining the centers of the sun and the earth with its projection on the equatorial plane. It happens because the earth rotates about an axis, which makes an angle of approximately 66.5° with the plane of its rotation around the sun. This δ varies from a maximum value of +23.45° on June 21 to a minimum value of -23.45° on Dec 21, zero on the two equinox days of March 21 and Sept 22. The declination angle can be found from the Cooper's equation (1969).

$$\delta(degrees) = 23.45\ sin[360/365(284 + n)];$$ (5.2)

Where,

n = day of the year.

3. Hour Angle (ω_s)

It is the angle measured in the earth's equatorial plane between the projection of the distance to the centre of the earth and the projection of a line from the centre of the sun to the centre of the earth. It is an angular measure of time and is equivalent to 15° per hour, measured from noon, based on local solar time (LST) or local apparent time being positive in the morning and negative in the afternoon.

4. Slope (β)

It is the angle made by the plane surface with the horizontal, taken to be positive for surfaces sloping towards the south and vice-versa.

5. Altitude Angle (α)

It is a vertical angle between the projection of the sun's rays on the horizontal plane and the direction sun's rays (passing through the point). That means, it is the angle between the object and the observer's local horizon. It is expressed as an angle between 0 degrees to 90 degrees.

$$\alpha = 90° - \Phi + \delta;$$ (5.3)

Where,

Φ = latitude.

δ = declination angle.

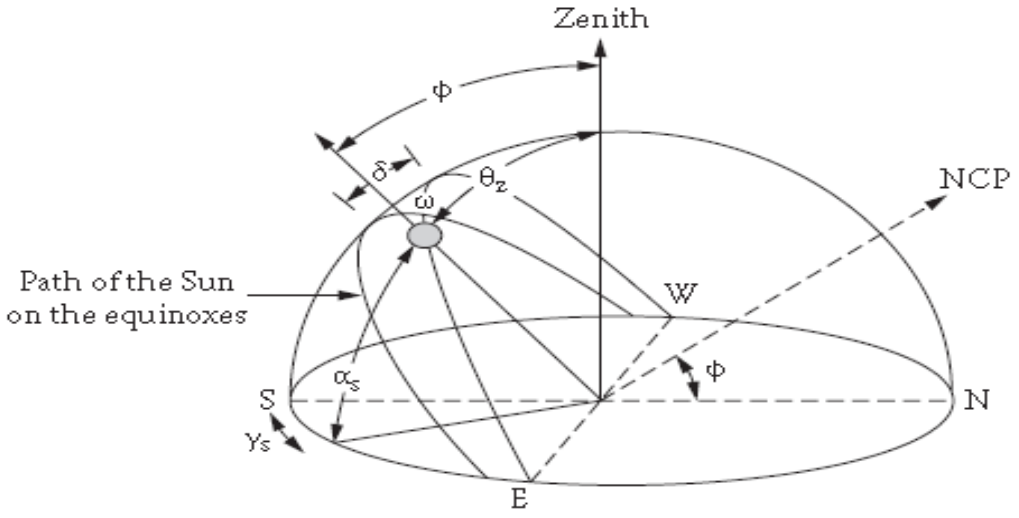

Fig. 5-3: Position of the Sun in the sky relative to the solar angles [89]

6. Zenith Angle (θ_z)

It is the complementary angle of sun's altitude angle. It is a vertical angle between the sun's rays and a line perpendicular to the horizontal plane through the point i.e. the angle between the beam from the sun and the vertical.

$$\theta_z = (\frac{\pi}{2} - \alpha); \quad (5.4)$$

$$cos\theta_z = sin\alpha; \quad (5.5)$$

Where,

α = altitude angle.

7. Solar Azimuth Angle

It is the solar angle in degrees along the horizontal east west of north or it is a horizontal angle measured from north to the horizontal projection of the sun's rays. Angle is positive when measured west wise. By convention, the azimuth angle is positive in the morning with the sun in the east and negative in the afternoon with the sun in the west. The location of the sun at any time of day can be described in terms of its azimuth angle. For solar work in the Southern

Hemisphere, azimuth angles are measured relative to north. The azimuth angle of the sun depends on the latitude, day number, and, most importantly, the time of day. From a derivation by T. H. Kuen *et al.* (1998), the equation can be written as:

$$sin\ \varphi S\ =\ cos\ \delta\ sinH\ \frac{cos\ \delta\ sinH}{\cos\beta} \qquad (5.6)$$

Where,

H = hour angle

δ = declination angle

β = slope

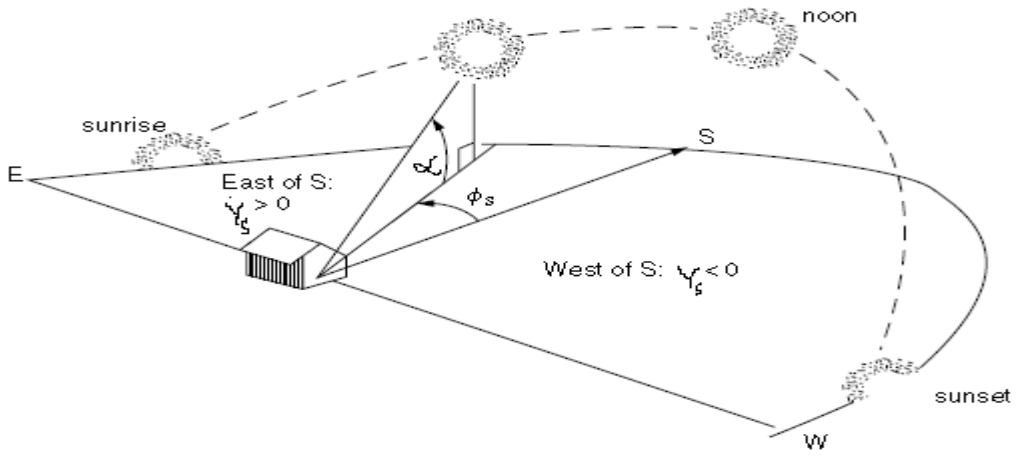

Fig. 5-4: The sun's position can be described by its altitude angle α and its azimuth angle Ys. By convention, the azimuth angle is considered to be positive before solar noon [89]

Tilt Factor

The ratio of the beam radiation flux falling on a tilted surface to that falling on a horizontal surface is called the tilt factor for beam radiation. For the case of a tilted surface facing south (Ys = 0°),

$$\cos\theta_z = \sin\delta\sin(\varphi-\beta) + \cos\delta\cos\omega\cos(\varphi-\beta) \quad (5.7)$$

Where,

θ_z = zenith angle.

δ = declination angle.

β = slope.

ω = hour angle.

φ = azimuth angle.

Anisotropy index

The anisotropy index, with symbol A_i, is a measure of the atmospheric transmittance of beam radiation. This factor is used to estimate the amount of circumsolar diffuse radiation, also called forward scattered radiation. It is a major component in the calculation procedure of solar radiation and it can be evolved by beam radiation.

Final factor

The final factor we need to define is a factor used to account for 'horizon brightening', or the fact that more diffuse radiation comes from the horizon than from the rest of the sky. This term is related to the cloudiness.

Nominal Operating Cell Temperature

The temperature of each panel at an irradiance of 800 W/m2 and an ambient air temperature of 20°C and wind speed is 1 m/s at a module tilt angle 45°C. NOCT is a very critical parameter that is required by various performance, qualification and energy rating standards/methods. It can be used with the maximum power temperature coefficient to get a better real-world estimate of power loss due to temperature increase. The cell temperature of open-rack panels, however, is governed by several external factors such as ambient temperature, irradiance level, wind speed, wind direction, and tilt-angle of the panel in an array. The difference in cell temperature and ambient temperature is dependent on sunlight's intensity (W/m2). For example, if a particular

panel has an NOCT of 40°C and a maximum power temperature coefficient of -0.5%/°C, power losses on temperature can be estimated at about 7.5%(=0.5% x (40°C – 25°C)).

5.2.1. Complete Specification of the Solar Panel

There are various types of characteristics in a Solar PV panel. They are of some specific ratings, different parameters are there. For different panel the electrical characteristics should be different. Also there are some temperatures co-efficient that are very much important to calculate the solar panel output power from the solar radiation data. The total characteristic features of the panel that is chosen for the proposed hybrid system has been shown below.

Table 5-1: Electrical Characteristics

STC Power Rating P_{mp} (W)	150
Open Circuit Voltage V_{oc} (V)	42.8
Short Circuit Current I_{sc} (A)	4.75
Voltage at Maximum Power V_{mp} (V)	34.0
Current at Maximum Power I_{mp} (A)	4.45
Panel Efficiency	11.9%
Fill Factor	73.8%
Power Tolerance	-3.00% ~ 3.00%
Maximum System Voltage V_{max} (V)	600
Maximum Series Fuse Rating (A)	15

Table 5-2: Temperature Coefficients

Temperature Co efficiency of I_{sc}	0.065 %/ºC
Temperature Co efficiency of V_{oc}	-0.38 %/ºC
Temperature Co efficiency of P_{mp}	-0.50 %/ºC

Table 5-3: Mechanical Characteristics

Cell Type	Monocrystalline Cell
Cell Size(mm)	125 × 125
Cells	6 × 12
Dimensions	1595.0 × 790.0 × 50.0mm (31.1 × 62.8 × 2.0 inch)
Weight	15.4Kg (34.0 lbs)

Table 5-4: Operation Conditions

Nominal Operating Cell Temperature (NOCT)	47.0ºC
Operating Temperature	-40.0ºC to 85.0ºC
Maximum Load	2400
Fire Safety Rating	Class C

5.2.2. PV Array System

The incorporation of the PV system along with the other renewable energy sources like wind energy and conventional energy sources like diesel generator, will help to find a suitable electricity access in case of remote areas, where the grid extension has not been possible yet. It can be used as a power sources for rural electrification if-

- Main grid is far away from the area.
- Status of electrification is too difficult (desert area, hilly area).
- Extension of grid is very costly.
- Density of consumer is very low.

The main advantages and disadvantages of the PV-array energy system are:

Advantages

- Fuels and water are not required.
- Eco-friendly and pollution free (no emission).
- Long lifetime at around 25 years.
- Low running cost and minimum maintenance is required.
- No restriction on harvesting the energy as far as there is sunlight.

Disadvantages

- High capital cost or starting cost.
- Large area required for installation.
- Can't work in the absence of sunlight.
- Generates DC output. So inverter is needed.
- Can't generate stable output with changing weather conditions.

In the process of generating energy from the solar radiation, the PV-arrays trap the photon particles of solar light and convert the light energy into electrical energy. The energy found from the PV-systems can be used in several applications. The output of the PV-arrays is DC form of energy. So, it can be directly used in the DC appliances. For AC appliances, this DC power has to be changed into AC form with the help of power electronic inverters.

5.2.3. System Configurations

In the stand-alone hybrid power systems, PV-array system is modeled in such a way that load demands can be met always efficiently. The intensity of the radiations that comes from the solar energy varies with time and season. So, to make the system much efficient and reliable, energy storage device like battery is connected with it in such a manner that loads can be supplied in any consequence and the battery can store energy whenever there is excess supply from the PV-array system. Then, the stored energy in the battery can be discharged during that time when there is a deficit of generated power.

Generally, most of the electrical devices or appliances can be operated by AC power source. However, the PV-array system can only give DC power. Thus, an inverter (DC/AC converter) is used so that AC loads can be supplied from the PV-system.

5.3. Wind Turbines

The generation of wind energy primarily depends on the atmospheric wind speed. The turbine should be installed or mounted on a tall tower to improve the wind energy output. Wind is an intermittent resource of energy and very much dependent on the nature. But still it is a reliable source of energy. It is known that in case of conventional energy system the fuel efficiency is only (30-40) % due to heat losses and different pollutions. But modern wind turbines can absorb more than 90% of available energy from wind. So this system has become very much efficient [90].

The main advantages and disadvantages of the Wind Turbine system are:

Advantages

- Eco friendly.
- No emission at the time of generation.

- No traditional fuel required.
- Operating and maintenance cost is low.
- Long lifetime up to 20 years.

Disadvantages

- Installation cost is very high.
- The wind speed in which the output depends varies time to time.
- Interference with radio/TV signals if located inappropriately.

The rotor is the main part of a wind turbine, which is the also the prime mover. The other part is generator. The rotor is connected to the generator via a gearbox which matches and enhances the rotational speed. Wind energy and solar energy are very much discontinuous in type. So using this energy alone a system should not be always that much efficient. So hybrid system combining of wind and solar power can be designed along with storage battery that can deliver power when there is no wind or sunlight or shortage of those sources in the system. Some important definitions regarding to wind speed energy are as follows:

Cut-in Wind Speed

The speed, when wind flows very gently at a low rate and cannot provide sufficient torque to rotate the blade of the turbine is called cut-in wind speed. With the increment of the wind speed gradually the turbine starts rotating and generating power. The range of the cut-in speed is generally between 3 and 4 m/s and in this speed the turbine first start to rotate.

Rated output wind speed

After crossing the cut-in speed limit of the wind turbine the turbine can generate electric power much faster and this increases rapidly as it is cubic function to speed. However, from the manufacturer point of view depending on the type of turbines, there is a limit when the turbine can generate maximum amount of power or the rated power. The wind speed at which the turbine can deliver rated power is called the rated output wind speed. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. In case of large wind turbine to keep the power output constant the blade angles are adjusted.

Cut-out Wind Speed

After crossing the rated wind speed limit the force exerted by the turbine is very high. So there will be a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This speed is called cut-out speed when the turbine stops rotating and it is generally 25 m/s.

Generally, if wind speed is between the rated speed and the furling (cut-out) speed of the wind turbine, the power output will be equal to the rated power of the turbine and if the wind speed is either less than the cut-in speed or greater than the furling speed of the wind turbine, then the output power will be zero.

5.3.1. Complete Specification of the Wind Turbine

Wind Turbines also have some distinct characteristic specifications on which the wind output generally depends. The features of different part of the turbine like rotor, blades etc. are also included in the study. The parameters are shown next.

Table 5-5: Performance parameters

Rated Electrical Power	20000W @ 10.5m/s
Rated Wind Speed	10.5 m/s
Cut-in Wind Speed	3.5 m/s
Cut-out Wind Speed (high wind)	23 m/s
Peak (survival)	50 m/s

Table 5-6: Rotor Features

Type of Hub	Fixed Pitch
Rotor Diameter	10.5m
Swept Area	86.54 m²
Number of Blades	3
Rotor Speed @ rated wind speed	140 RPM
Location Relative to Tower	Down Wind
Rotor Tip Speed	47 m/s
Design Tip Speed	7

Table 5-7: Blade Features

Length	5 m
Material	Class Fiber
Airfoil (type)	NACA 44012
Twist	16° outer blade
Root Chord	150 mm
Max Chord	450 mm
Tip Chord	160mm
Blade Trailing Edge	Tapered and Straight
System Weight	950 Kg
Blade Weight -approx	75 Kg

Table 5-8: Generator Features

Type	PM Alternator
Voltage for Battery Charge Sys	415 - 3 Phase
Rectifier	Applicable
Watts @ Rated Wind Speed	20000 Watts
Rated Generator RPM	150
Speed RPM (nominal)	200
Battery Bank (Min)	12-v 150 Ah - 20 No's

Table 5-9: Transmission Features

Type	Direct Drive
Ratio (rotor to gen. speed)	1 to 1
Lubrication	Grease

Table 5-10: Yaw System Features

Normal	By Tail Vane with Slip Ring
Structural	Yaw bearing mounted on tower top

Table 5-11: Tower Features

Type	Lattice type
Tower Height	25 m
Options	30 m

Table 5-12: Control System

Type	PLC Based
Over speed Device	Mechanical Governor
Manual Brake	Electro Magnetic

Table 5-13: Inverter Features

Type	Sin Wave
Inverter Output Voltage	415 V AC

5.4. Energy Storage System

Now a day's energy storage system has taken a huge part in case of power generation. It makes the system much more reliable and efficient. In hybrid power system also the connection or combinations of different sources are done, taking the energy storage system into account.

The need of energy storage is to transfer the storage power to the system, when there is a deficit of generated power occurs. During excess supply from RESs this energy storage system can store energy [91, 92]. First, the energy generated from the RES has to be changed to a storable form of energy when there is excess energy and then it is supplied at the time of shortage in generation. This can be shown by the following block diagram.

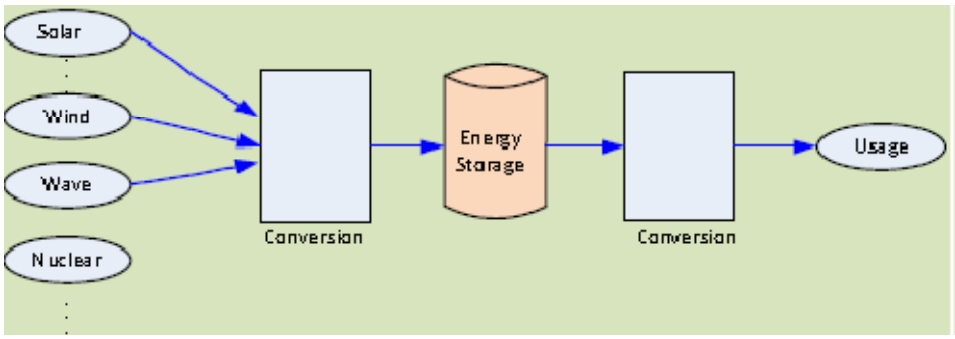

Fig. 5-5: Energy storage with distributed energy system [91]

The hybrid power system comprises of PV array, Wind Turbine, Battery and Diesel generator. As the solar and wind energy both are not continuous energy source, so the generation from the PV and Wind Turbine may be discontinuous. In a HPS, both the RESs and the load are varying throughout the day. These variations can cause a power imbalance in the system. As a result, the voltage and frequency in the power system will be affected. The addition of energy storage will assist balancing the distribution of power in the power network.

The different energy storage techniques have different applications in power systems. Some of them are [91]:

i. Rapid reserve.
ii. Area control and frequency responsive reserve.
iii. Commodity storage.
iv. Transmission system stability.
v. Transmission voltage regulation.
vi. Transmission and Distribution facility deferral.
vii. Renewable energy management.
Viii. Customer's energy management.
ix. Power quality and reliability.

5.5. Energy Storage Battery Bank

The two renewable energy sources wind and Solar PVs are the intermittent sources of energy that means they cannot give power to the system all through the day. So it is very much essential to incorporate energy storage in such hybrid power systems. Energy storage can smooth out the fluctuation of wind and solar power and improve the load availability [Borowy *et al*, 1996].

Battery bank is an electrochemical device which uses electrochemical reactions to store electricity in the form of potential chemical energy. The energy storing batteries used with HPSs are rechargeable in a sense that they can charge when there is enough supply from the RESs and discharge when there is larger load demand than there is supply. They are sometimes also called as secondary batteries. The charging time for the battery bank is:

$$t_{charge} = \frac{BC}{I_{rated,source}}(hr) \tag{5.8}$$

Where,

t_{charge} = charging time of the battery (hr).

BC = Battery Capacity (Ah).

$I_{rated,source}$ = Rated source current (A).

5.5.1. Battery Characteristics

Battery capacity

This is the amount of energy, the battery can store. The amount of energy that can be extracted from a fully charged battery basically depends on temperature, rate of discharge, battery age and battery type. The three main ratings to specify the capacity of a battery are:

- *Ampere-hour (Ah)*: the amount of current at which the battery can discharge their stored energy over a fixed interval of time.

- *Reserve capacity*: the time length in minutes when the battery can manage to produce a specified level of discharge.
- *KWh capacity*: the amount of energy required to charge a depleted battery. However, depleted batteries are not fully discharged batteries.

Battery voltage

The battery voltage is that of a fully charged battery. It depends up on the number of cells and voltage per cell. The battery voltage decreases when the battery starts discharging.

Cycle depth

Fully discharging batteries can cause an adverse effect regarding to the life of the battery. Deep-cycle batteries can discharge up to 15%-20% of their capacity. This gives a depth of discharge of 85% - 80%.

Energy density/Specific energy

It is the amount of energy that can be taken from a battery per unit of battery weight or volume. By default, deep-cycle batteries provide the potential for higher energy densities than non-deep cycle varieties since more of the energy in the battery can be extracted (e.g. larger acceptable DOD).

Power density/Specific power

Power density is the amount of power that can be taken from a battery per unit of battery weight or volume.

Autonomy

This can be defined as the ratio of restorable energy capacity to the maximum power discharge. It indicates the maximum amount of time in which the system can extract its energy. The autonomy of a system depends on the type of storage and the type of application.

$$a = \frac{E_{restore}}{P_{discharge}} \quad (5.9)$$

Durability (cycling capacity)

Energy storage systems are arranged in such a manner that the system can release the energy after every recharge. The number of times the energy storage can release the energy level it was designed for after each recharge is referred to as durability or cycling capacity. It is expressed in number of cycles denoted as $Ncycles$. The cycling capacity mainly depends on the depth of discharge. The higher the DOD, the lower will be the cycles and the lifetime of the batteries.

5.6. The power inverter

The power electronic circuit or device that means inverter helps to maintain the system reliability properly and to synchronize the system in a definite manner. It is used to convert DC power into AC power form at the desired frequency load. The DC input that comes to the inverter can be from several sources. It depends on the system design or the connection topologies that from which sources the inverter receives energy. The sources may be the following:

DC output of the Solar PV array.

DC output of the energy storage batteries which delivers power at the time of deficit.

Taking power from these sources it converts it into AC power and can maintain the system reliability. In this study, the efficiency of the inverter is constant and has been taken as 0.9. The inverter's efficiency is used for calculating batteries charging and discharging power.

5.7. Diesel Generator Set

Diesel Generator is one of the major components of the HPSs. After delivering the power through PV, Wind Turbine and Battery, if still there is a requirement of power, then DG starts working. A diesel generator is a diesel engine combined with an electrical generator (alternator) via a rotating part to generate electric energy. The diesel engine can convert the chemical energy

to mechanical energy. The chemical energy that comes from the fuel can be converted to the mechanical power which can rotate the shaft of the engine that is connected to the alternator. Generally, the prime mover can deliver the amount of power that is within the permissible limit that means up to the rated power. The synchronous generator which is connected to the prime mover can maintain the voltage constant at any load condition. The diesel generator is used to generate electric energy in places where:

- There is no grid connection.
- Grid cannot supply the full power demand.
- In case of uninterruptible supply of power.

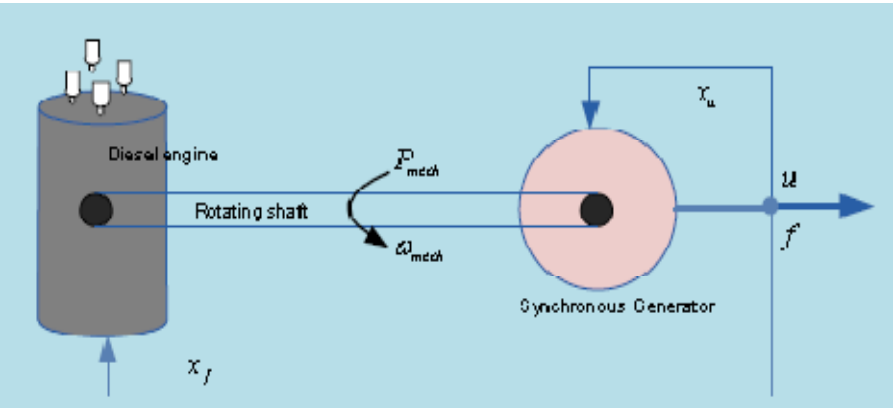

Fig. 5-6: Schematic diagram of Diesel Generator with constant engine speed [93, 94]

The AC power output can be produced by a synchronous generator at that time when the turbine is rotated with the effect of a prime mover that is connected to the diesel engine shaft. The speed of the diesel engine is constant and it can maintain the output voltage frequency which is 50 Hz to 60 Hz. By controlling the excitation current the synchronous generator can control its output voltage. Diesel Generators have some drawbacks also. These are:

- Very much noisy at the time of operation.
- Very heavy and difficult to handle.
- Efficiency is very low.
- Can cause air pollution that means not eco-friendly.

Chapter 6: System Integration and Design

6.1. Introduction

This chapter describes the system integration and design of the different components of test system. The test system is comprised of solar photovoltaic, wind turbine, battery, diesel generator and converter for converting the DC output of solar and battery and simulated with the help of advanced meta-heuristic optimization method called particle swarm optimization technique (PSO) and feasibility analysis of the model system is being done on a test location in West Bengal, India. Initially, test location is investigated and social-economical condition and different renewable resources data has been studied. It is seen that the area is endowed with plenty of renewable sources. Then the test system is formulated and integrated to form the hybrid system keeping in mind the geographical features of that location. Specifically the Sundarbans Island region of India has been chosen for the study. There are various reasons for selecting this region which are as follows:

- India is one of the largest populated developing countries among the world. That's why the load demand of this country is also very high. So in this present situation, to maintain balance with the random increasing load demand, remote areas electrification with renewable energy is really needed.
- The adverse implications, particularly related to atmospheric pollution caused by the fine particulate fractions associated with their dependency on fossil fuel burning, biomass burning, and also the dearth of proper conventional sources is of most concern when one considers their impact on the rich and unique biodiversity of the Sundarbans. Infact, the Sundarbans, one of the world's largest mangroves represents an area infested with a host of rare and endangered species. But still on that region, a huge amount of area is still un-electrified. Though around 50000 of households are already using renewable energy as their power source [95]. But most the systems providing carbon free energy is stand-

alone single energy system mostly solar PV sometimes integration of battery and diesel generator with it. But hybrid system comprising different renewable energy sources is still to operate in this region [97]. So it will surely enhance the chances to develop and construct hybrid renewable electrification projects in those regions which are still without electricity.

- The local electrification authority West Bengal Renewable Energy Development Agency (WREDA) has been continuously taking different steps and trying to deploy various kinds of renewable energy technologies (viz. solar PV panel, Wind-diesel-battery, Wind-diesel-biomass, biomass gasification etc.) in the islands. This work will also enhance the deployment of different hybrid renewable energy system and make organizations/authorities interested to take up different new projects.

6.2. Sundarbans Island

Literally the word 'Sundarban' means 'beautiful forest'. From Hooghly river mouth (India) to the Meghna river mouth (Bangladesh) along the Bay of Bengal, the long 260 km stretched area of the lower part of the Ganges delta has formed this Island. The Island consists of a vast area of forest and saltwater swamp. The World's largest mangrove forest area of 10,000 km is also situated there [95]. Different types of rare endangered species like tigers, birds, aquatic mammals, reptiles etc. live here. A large amount of 9630 square km area of Sundarban has been declared as "Sundarban Biosphere Reserve" by Government of India. The total forest area is 4264 square kilometers out of which 1810 square kilometers are wetland [95].

The latitude and longitudinal position of the Sundarban region, situated in the portion of India is within 21°32′N - 22°40′N and 88°00′E - 89°00′E respectively. This region is placed within a distinct boundary such as: Hooghly River in the west, Ichhamati, Kalindi, Raymangal Rivers in the east, Dampire-Hodges line in the north and Bay of Bengal in the south. Annual average temperature and rainfall of this area is around 25°C and 1920 millimeters respectively while average humidity is about 82%. About 4 million people live in the Indian side of Sundarban. The area comes under the state of West Bengal within two administrative districts South 24 Parganas and North 24 Parganas. There are 13 blocks within South 24 Pargana and 6 blocks within North 24 Pargana [95].

Sensitive eco-system, very poor infrastructure and remoteness are the main features of that region. Access to electricity is one of the major problems of this island. Extension of transmission grid from the main lands to these islands is very much difficult due to wide rivers or creeks resulting in technical limitations and prohibitive cost. For their daily living purposes people used to purchase expensive kerosene oil which is also non-reliable. In some villages, diesel generators are used to supply electricity. But this is also not reliable because of unavailability of fuel. Since 1993, West Bengal Renewable Energy Development Agency (WREDA) has taken a step to work for the rural electrification by renewable energy. So far WBREDA has been able to supply electricity to almost 40,000 households through 16 SPV mini-grid supplies, approximately 770 kW and more than 35,000 standalone home lighting systems [96].

6.3. The Case Study Location: Laxmijanardanpur

Laxmijanardanpur village is under Pathar Pratima Community Development Block of South 24 Parganas District in Indian Sundarban. In the project this area is selected as the target area. The focus area may be a real simulation of almost all the villages of that region as the characteristic features of all the villages of Sundarban region are nearly same. The several socio-economic data of this village has been studied and shown below [96]:-

latitude	21°46´N
longitude	88°20´E
Total no of households	753
Average monthly income of a household	2117 rupees
Rs 1001-2000 income groups	53.7%
Below Rs 1000 income groups	19.3%
Rs 2001-3000 income groups	17.3%

Above Rs 3000 income groups	9.7%
Average household size	6 persons
1 – 3 members	13.4%
4 – 6 members	60.8%
7 – 9 members	7.8%
Above 10 members	8.0%
Occupation of cultivation	55.4%
Daily labour	32.3%
Business	7.2%
Other jobs	5.2%
Average per head expenditure in kerosene oil	13.9 rupees/month
Expenditure below Rs 10 per day	42.9%
Expenditure between Rs 11-20 per day	41.1%
Expenditure exceeds Rs 20 per day	16.0%
SPV HLS installed households	26.0%
SPV through mini-grid supply	40.0%

The above data are the true representation of the socio-economic condition of the village and characteristic of the habitat. Days are changing and the load demand of that area is rapidly increasing. To combat that demand, establishment of standalone renewable hybrid energy generating system is very much necessary. So in this chapter different renewable energy sources along with their availability, a standalone hybrid energy system has been proposed to check the feasibility of the system for that particular location.

6.4. Model Design for Standalone System

A Hybrid system is a combination of different renewable or conventional energy sources. The proposed hybrid model comprises of PV-Wind-Battery-DG. The main components are PV module and wind turbine to supply the demand and battery and diesel generator are used as the back-up energy sources. The PV module and batteries are giving the DC power output which is going to the DC link and then is converted to AC power by the inverter. On the other hand, wind turbines and the diesel generators are giving the AC power output which is directly going to the AC link. The system is optimized considering the maximum load profile of the locality which the system can experience over the next 25 years. Next 25 years' worst hourly profile of average wind speed and solar radiation is projected for that specific location. The overall system design has been shown in the following section where it can be seen that all the renewable and the back-up sources are selected judiciously. After the selection of different components, the model system is integrated with the solar PV, wind turbine, battery and DG and designed to meet the local demand of that area.

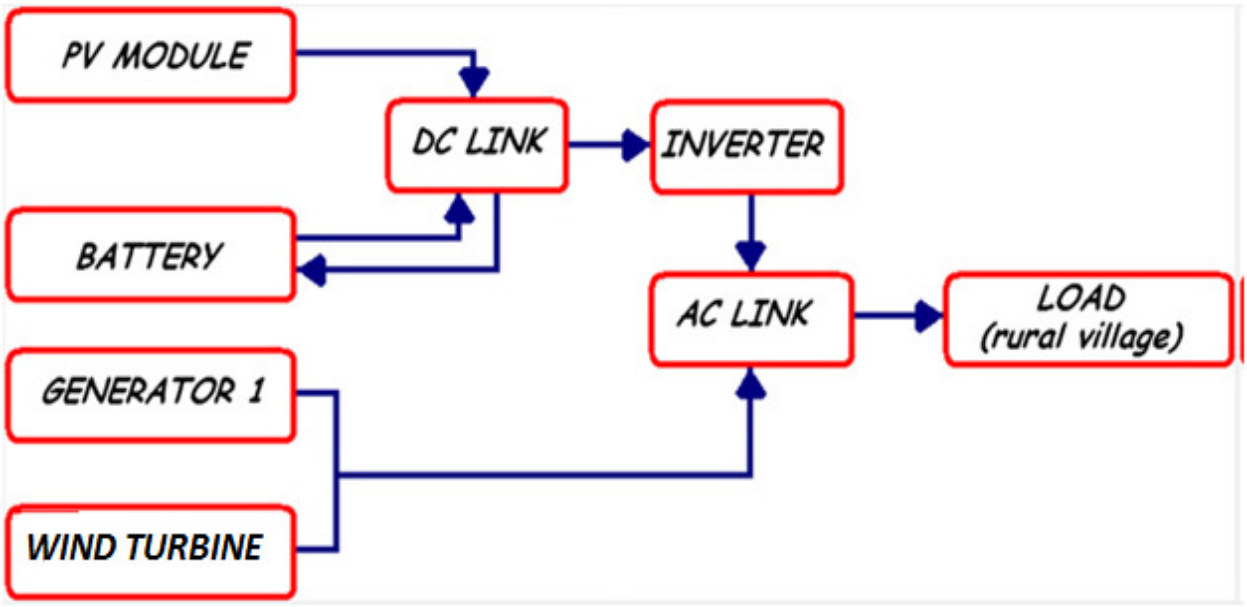

Fig. 6-1: Standalone hybrid energy system model

6.4.1. Renewable and Back-Up Energy Resources

In our study there are two renewable energy sources of solar energy and wind energy. Apart from that, energy storage battery bank and also conventional diesel power sources are used as a backup source.

6.4.1.1. Solar Resource

Sundarban area is rich in solar resources. All the part of the island receives a consistent amount of solar radiation during the whole year. The average annual solar radiation is about 1800 KWh/m² on horizontal surface [97]. Throughout the year, almost 250 sunny days and 55 overcast days can be found on that region. The annual average solar radiation on horizontal surface is about 4.91 KWh/m² per day [97]. The ranges of daily global solar radiation in different months are different.

For calculation of the power output from the solar PV array for this specific location, different types of solar angels, the latitudinal and longitudinal sun position, and many solar co-efficient are taken into consideration. With the help of the measured data of 24 hours, solar power output profile has been made.

6.4.1.1.1. Calculation of Solar Radiation

For calculation of solar PV output, following steps are followed:

- **Latitude of the area**

  First the latitude of particular concerned area is found out from the meteorological data. The latitude of the test location is 21.76°.

- **Declination angle calculation**

  The declination angle is represented as:

$$\delta\ (in\ degrees) = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \quad (6.1)$$

  Where, n = day of the year.

  For the current thesis work, n is taken as 183 and δ is obtained as 14.87° or 0.259 radian.

❖ **Hour angle calculation**

The exact calculation of the hour angle is:

$$\cos \omega_s = (-tan\Phi \times tan\delta) \quad (6.2)$$

Where,

Φ = latitude.

δ = declination angle.

From the above equation, hour angle is derived as 83.91°.

❖ **Day length calculation**

As 1 hour equals 15° of the sun traveling through the sky, the number of daylight hours (N) is determined by solving the following equation for ω_s and converting the resultant degrees into hours and day length calculated value is 11.18.

$$N = \frac{2}{15} \cos^{-1} (-\tan \Phi - \tan \delta) \quad (6.3)$$

Where,

Φ = latitude.

δ = declination angle.

❖ **Angle of incidence calculation**

The total angle of incident is evolved from the following equation:

$$\cos \theta = \sin \delta \sin \Phi \cos \beta - \sin \delta \cos \Phi \sin \beta \cos \gamma + \cos \delta \cos \Phi \cos \beta \cos \omega + \cos \delta \sin \Phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \quad (6.4)$$

The angle of incident for this particular area is 0.66782.

Where,

δ = declination angle.

Φ = latitude.

β = slope.

γ = azimuth angle.

ω = hour angle.

- **Zenith angle calculation-** (by setting $\beta = 0°$)

The complementary angle of the Sun's altitude angle, zenith angle is derived from below equation and obtained as 0.7298.

$$\cos\theta_z = \cos\Phi\cos\delta\cos\omega + \sin\Phi\sin\delta \quad (6.5)$$

Where,

Φ = latitude.

δ = declination angle.

ω = hour angle.

- **Extraterrestrial normal radiation calculation**

The total amount of extraterrestrial normal radiation is calculated from the following equation.

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \quad (6.6)$$

For the present study, Extraterrestrial normal radiation is 1321.89 W/m^2.

- **Extraterrestrial horizontal radiation calculation**

The total amount of extraterrestrial horizontal radiation is found to be 964.71 W/m^2 calculated from the following equation.

$$G_0 = G_{on} \times \cos\theta_z \quad (6.7)$$

Where,

G_{on} = extra-terrestrial normal radiation.

θ_z = zenith angle.

❖ **Average extraterrestrial horizontal radiation over the time step calculation**

The total amount of average extraterrestrial horizontal radiation is calculated from the following equation.

$$\overline{G_0} = \frac{12}{\pi} G_{on} \left[\cos \Phi \cos \delta \left(\sin \omega_2 - \sin \omega_1\right) + \frac{\pi}{180^{\circ}} \left(\omega_2 - \omega_1\right) \sin \Phi \sin \delta\right] \quad (6.8)$$

Where,

G_{on} = extra-terrestrial normal radiation.

Φ = latitude.

δ = declination angle.

ω_1, ω_2 = hour angle.

Depending upon the calculated values of δ,Φ, normal solar radiation and taking the values of $\omega_2$and ω_1 as 90° and -75° respectively , average extraterrestrial horizontal radiation is obtained as 10283.469 W/m^2.

❖ **Regression co-efficient calculation**

The regression co-efficient can be different for different locations. Rietveld proposed an equation for measuring this co-efficient which is:

Rietveld Equation

$$a = 0.10 + 0.24 \left(\overline{n}/\overline{N}\right) \quad (6.9)$$

$$b = 0.38 + 0.08 \left(\overline{N}/\overline{n}\right) \quad (6.10)$$

Where,

a & b are the regression co-efficient.

For the present work, regression co-efficient values are obtained as 0.512 and 0.539 respectively.

❖ **Global solar radiation calculation**

The monthly global solar radiation $\bar{G}/\overline{G_0}$ falling on a horizontal surface at this location is which is given by the equation below:-

$$\bar{G}/\overline{G_0} = a + b\,(\bar{n}/\bar{N}); \quad (6.11)$$

Where,

a & b are the regression co-efficient.

❖ **Clearness index Calculation**

K_t is the clearness index. (Duffie and Beckman 1991, Frere *et al.* 1980).

$$K_t = \bar{G}/\overline{G_0} \quad (6.12)$$

Here, clearness index is 0.8197.

Where,

$\bar{G}$ = global horizontal radiation.

$\overline{G_0}$ = average extra-terrestrial horizontal radiation.

❖ **Beam radiation calculation**

The total amount of beam radiation calculated for the test location is 5743.3673 W/m^2 from the equations.

$$\bar{G} = \overline{G_b} + \overline{G_d} \quad (6.13)$$

$$\overline{G_b} = \bar{G} - \overline{G_d} \quad (6.14)$$

Where,

$\bar{G}$ = global horizontal radiation.

$\overline{G_d}$ = monthly mean of the daily diffuse solar radiation.

❖ **Diffuse fraction calculation-**

The calculation of diffuse fraction is measured by [98]:

$$\frac{\overline{G_d}}{\bar{G}} = \begin{cases} 1.0 - 0.09K_t & ;\ K_t \leq 0.22 \\ 0.9511 - 0.1604K_t + 4.388{K_t}^2 - 16.638{K_t}^3 + 12.336{K_t}^4 & ;0.22 \leq K_t \leq 0.80 \\ 0.165 & ;\ K_t > 0.80 \end{cases} \quad (6.15)$$

The ratio is calculated as 0.22071.

Where,

K_t = clearness index.

❖ **Beam radiation component calculation**

The beam radiation component is derived from the following calculation.

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (6.16)$$

The value of R_b is 0.91507.

Where,

θ_z = zenith angle.

❖ **Anisotropy index calculation**

This index depends on the following equation:

$$A_i = \frac{\overline{G_b}}{\overline{G_0}} \quad (6.17)$$

In this study this anisotropy index is obtained as 0.5585.

Where,

G_b= monthly mean of the daily beam radiation.

$\overline{G_0}$ = average extra-terrestrial horizontal radiation.

❖ **Final factor calculation**

The calculation of final factor is given as:

$$f = \sqrt{\frac{\overline{G_b}}{\bar{G}}} \quad (6.18)$$

Here *f* is 0.88277.

Where,

$G_b =$ monthly mean of the daily beam radiation.

$\bar{G} =$ = global horizontal radiation.

❖ **Total global radiation calculation**

The total amount of global radiation in which the output of the Solar PV depends is defined as:

$$\overline{G_T} = (\overline{G_b} + \overline{G_d}A_i)R_b + \overline{G_d}(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (6.19)$$

Where,

$\overline{G_T}$ = Total global solar radiation.

$\overline{G_d}$ = Monthly mean of the daily diffuse solar radiation [W/m^2].

A_i = Anisotropy index.

R_b = Beam radiation component.

β = slope of the surface [°].

f = final factor.

$\bar{G}$ = global horizontal radiation on the earth's surface averaged over the time step [kW/m^2].

ρ_g = ground reflectance.

From the above calculations, the amount of total global solar radiation falling on the earth surface or surface of the solar photovoltaic is calculated. Depending upon these values, the PV output is varied throughout the day. Though solar energy is an efficient renewable energy but

still for the variation of sun's position and different solar angles, earth cannot receive a steady amount of solar radiation throughout the daytime. And in the night time this radiation becomes zero due to the absence of sunlight. So, solar energy is intermittent in nature. The figure below shows the amount of solar radiation the system receives from the sun and also how the radiation is varying throughout the daytime on our test location. The x-axis denotes the time period of a day in hour and y-axis represents the amount of available solar radiation on the particular test location in Kw/m^2.

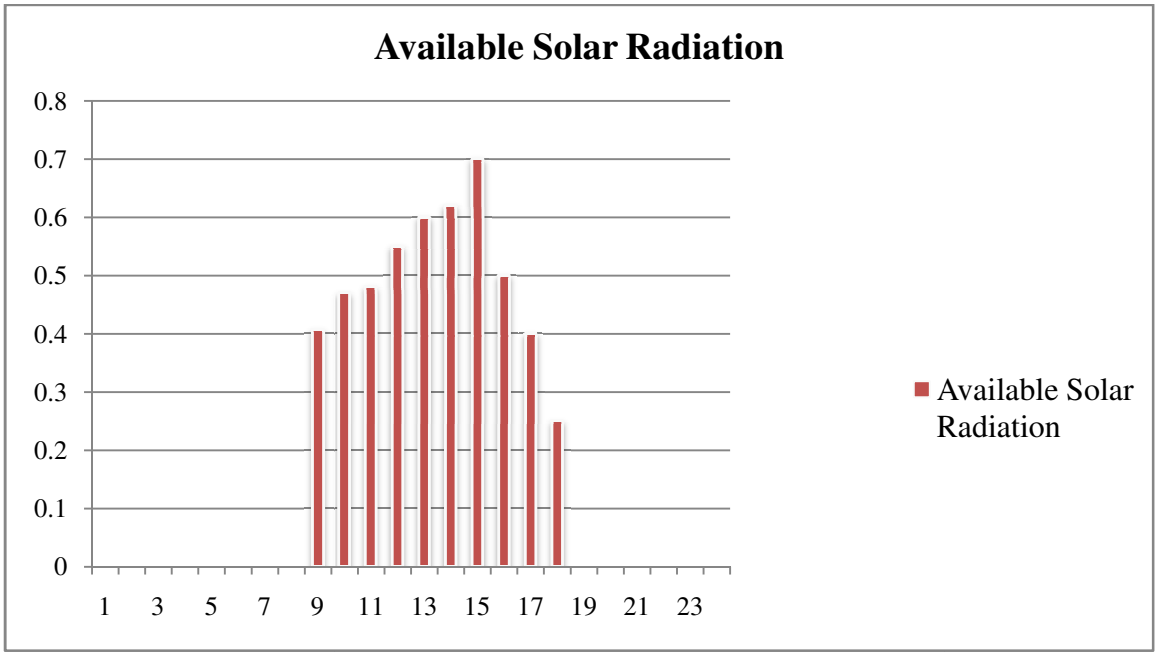

Fig. 6-2: Available Solar radiation data with respect to different hours of a day

6.4.1.1.2. Calculation of the Actual Power Output from the PV Module

The maximum power output from a PV panel at Standard Test Conditions (STC) (at 25^0C & 1000 W/m^2) which is usually labeled on the panel nameplate. The actual power output can be estimated by:-

– (6.20)

(6.21)

Where,

$\overline{G_T}$ = solar radiation on the panel surface.

$T_{ambient}$ = ambient temperature.

T_{noct} = the nominal operating cell temperature.

λ = maximum power temperature co-efficient.

The following table shows the exact electrical characteristics data that has been used in the optimization process to calculate the power output of the solar PV array. A 150W solar module (BP2150S), made by BP-Solar company is considered for the system. Solar modules are connected in series to obtain the PV array of 9 KW. The electrical characteristic of the solar module taken for present work is given in Table 6-1.

Table 6-1: Electrical characteristics data of the solar panel required for the optimization

Rating (watt)	150
PV derating factor	0.88277
Incident radiation at STC	1
Nominal operating cell temperature	47°C
Temperature co-efficient of panel	0.0043
PV cell temperature	25°C

Depending upon 24 hours solar radiation data, solar PV array power output profile has been made which is given in figure 6-3 and it can be seen that solar energy is not a continuous source of energy. Only for 10 hours a day, the solar PV panel is giving the solar power output.

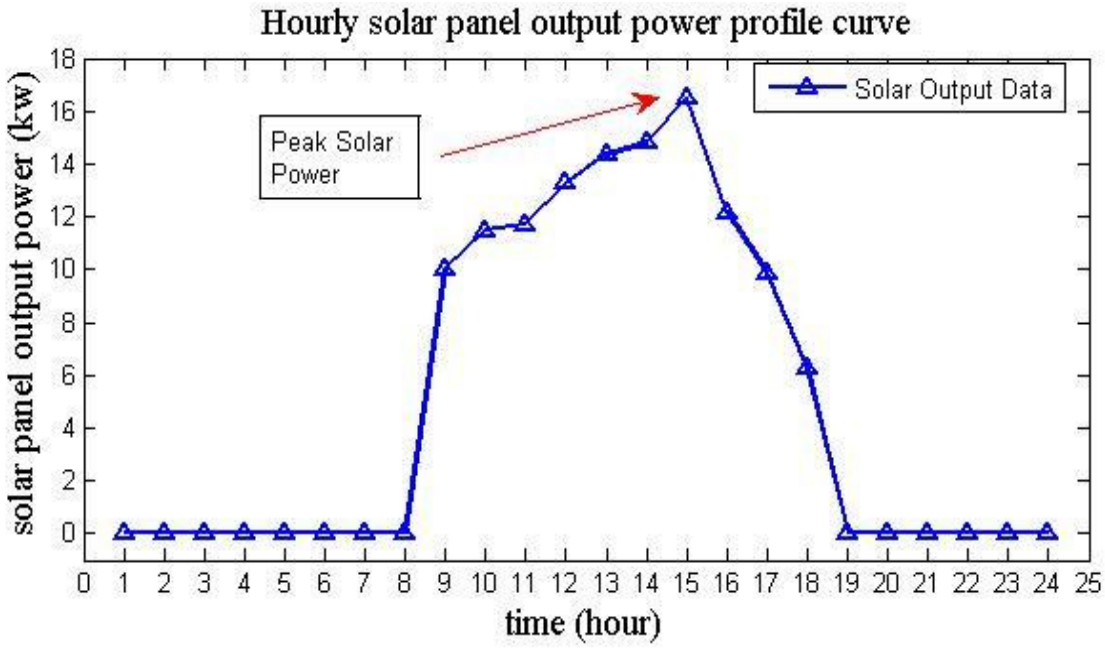

Fig. 6-3: Solar PV array output with respect to different hours of a day

6.4.1.2. Wind Resource

Wind energy is the most attractive, clean and commercially attractive renewable sources of energy. In order to harness wind energy in the State of West Bengal, WBREDA has collected wind data for the whole State. Only some coastal areas of West Bengal are suitable for Wind power generation. In the entire region of Sundarbans, CWET (Centre for Wind Energy Technology, Government of India) has installed wind-monitoring stations and published wind data of two locations only, one is Ganga Sagar and the other is Fraserganj. Both the places are situated at the sea-shore, so they get enough wind flow from the atmosphere. The Sundarban region is almost a flat region with mean altitude near mean sea level. So there is not much variation in terms of geographical features through the entire island. And also the absence of surface roughness and big buildings enhance the probability of steady wind flow. The average annual wind speed in this region exceeds 18 km/hour [97].

6.4.1.2.1. Variation of Wind Speed

The wind speed profile of 24 hours for the test location is obtained from official site of NASA and is given in figure 6-4. From the graph it can be seen that, at the early morning the system receives higher wind speed and gradually it decreases as the time elapses and again it is

increased a little during the night time. The speed of wind is a random process; therefore it should be described in terms of statistical methods. The wind speed data were recorded near the ground surface. To upgrade wind speed data to a particular hub height an equation has been evolved and is given below. As the installation height of the wind turbine has a large effect on the energy available from the system, the adjustment of the wind profile for height can be taken into account by using a height adjustment equation (Ilinka *et al.*, 2003).

— (6.22)

Where:-

V - Wind speed at projected hub-height, H.

- Wind speed at reference hub-height, .

- Power-law exponent (- 1/7 for open land).

The speed at hub height using above equation is calculated for the test location and given in figure 6-4. The x-axis denotes the time period of a day and the y-axis represents the available wind speed from the atmosphere on the test location.

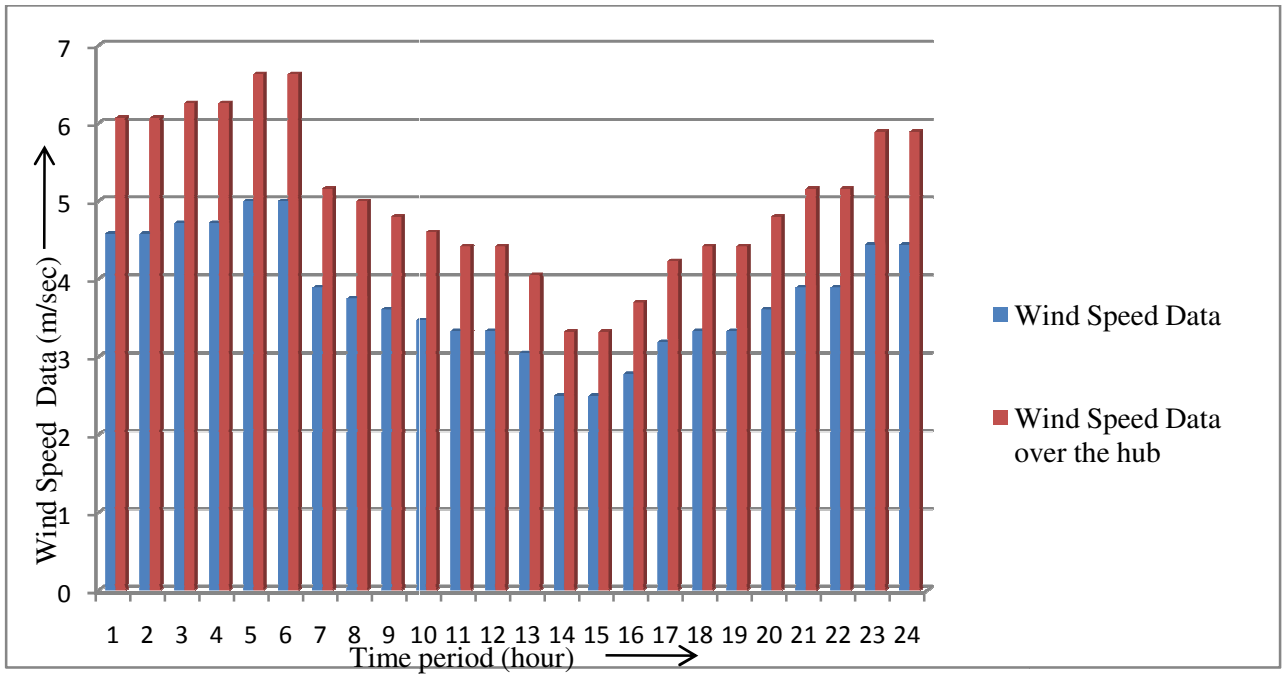

Fig. 6-4: Available wind speed data with respect to different hours of a day.

6.4.1.2.2. Power Output from Wind Turbine

The kinetic energy of the wind that is captured from the wind turbines and converted to electrical energy depends on the wind speed (wind potential) and the height of the wind turbine since the wind speed varies with the height. It must be stressed out that approximately (30-40) % (actually a coefficient up to Betz limit of 59%) of wind energy potential can be transformed to electrical energy at the horizontal axis wind turbines because of the mechanical losses of the turbines [90].

For a specific wind generator, a model should be developed according to its power output performance curve, which is given by the manufacturer.

In this study, the power law is applied for the vertical wind speed profile, as shown in equation below (Ilinka *et al.*, 2003) [21] for the calculation of power output from wind energy system. This power law exponent varies with the elevation, the time of day, the season, the nature of the terrain, the wind speed and the temperature.

The available wind generator power output is a function of the wind velocity *V*:-

$$P_{wt} = \begin{cases} 0 & ; V_w \leq V_{cutin}, V_w \geq V_{cutout} \\ P_{wtmax} \times \dfrac{V_w - V_{cutin}}{V_{rated} - V_{cutin}} & ; V_{cutin} \leq V_w \leq V_{rated} \\ P_{wtmax} & ; V_{rated} \leq V_w \leq V_{cutout} \end{cases} \quad (6.23)$$

Where:-

P_{wt} : electrical power output of the turbine.

P_{wtmax} : rated electrical power.

V_w : wind speed at hub height at test location

V_{cutin} : cut-in wind speed.

V_{rated} : rated wind speed

V_{cutout} : cut -off wind speed.

The generalized characteristics curve of P_{wt} versus wind velocity V has been illustrated next. In the graph, the fundamental wind speeds like cut-in speed, rated speed, cut-out speed all has been shown. Also it can be seen how the wind turbine power output varies according to the different wind speeds. The power output is zero below the cut-in speed; within the cut-in and rated speed the output increases rapidly as it is a function of speed; at rated speed the power output reaches the maximum output means rated power output of the turbine; within rated and cut-out speed the output becomes steady delivering the rated power output; over the cut-out or furling speed the output becomes zero again.

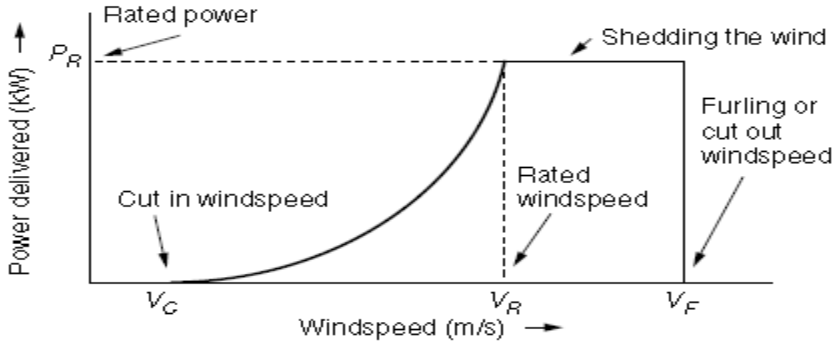

Fig. 6-5: Idealized power versus speed curve of the Wind Turbine

The following table shows the exact electrical characteristics data of wind turbine that has been used in the optimization process to calculate the power output of the wind turbine from the wind speed data. A 15KW wind turbine, made by Vaigunth Enertek (p) Ltd. is considered for the present study. It has a cut in speed, rated speed and cut out speed of 3 m/s, 10.5 m/s and 23 m/s respectively.

Table 6-2: Electrical characteristics data of the wind turbine required for the optimization

Rated output (KW)	15
Cut-in wind speed (m/sec)	3
Rated wind speed (m/sec)	10.5
Cut-out wind speed (m/sec)	23

Hub height (m)	30
Anemometer height (m)	4
Alpha co-efficient	0.14

The power output for 24 hours of the 15 kW wind turbine is calculated considering the speed at hub height and other parameters and is shown in figure 6-6. It can be seen from the graph that wind energy is not a continuous steady source of energy. As it is dependent on wind speed it varies a lot all along the day. So, the system also has received variable wind energy. During the whole day the wind turbine is giving the wind power output but at the early morning this output power is maximum and at noon this becomes minimum. Due to this intermittent nature of wind energy, it is almost impossible to form a system only with a wind turbine but it can be connected in a hybrid system to give reliable power generation.

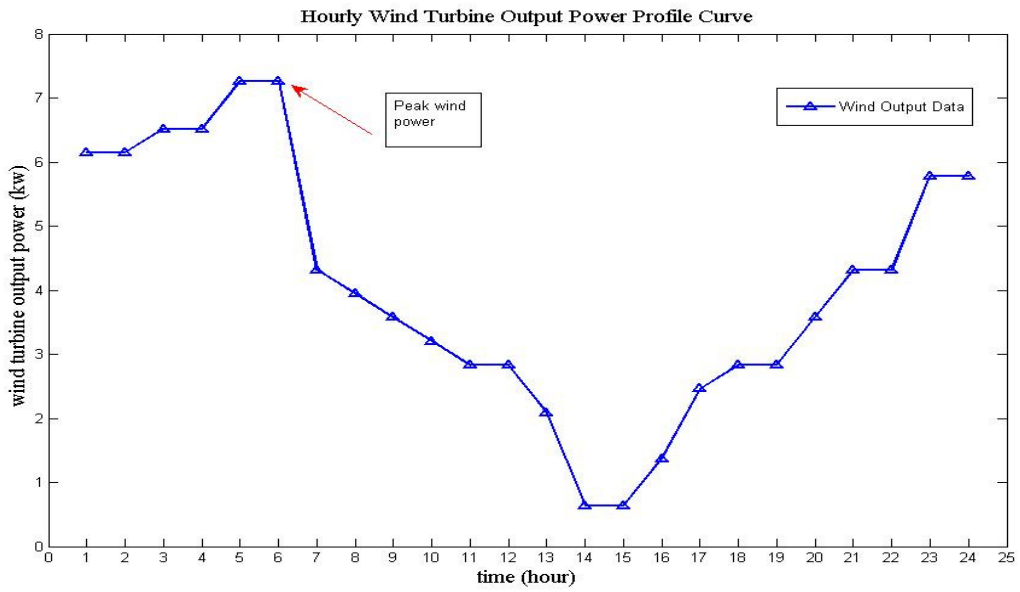

Fig. 6-6: Wind Turbine output with respect to different hours of a day

6.4.1.3. Battery

Batteries are one of the main components of the PV-Wind-Battery-DG hybrid system used to store energy at that time when there is excess amount of power generated by the solar PV and the wind turbine. It can deliver this stored energy to the system later when there is a deficit of the generated power occurs in the system.

6.4.1.3.1. Battery Sizing

There are some steps need to be mentioned following by which the battery size of the proposed hybrid system can be set. The batteries of 800Ah and 12V are considered for the proposed hybrid system. They have specific electrical characteristics which are required for the optimization procedure to find out the exact battery size. The method of calculating the battery size has been taken from the battery sizing worksheet of a solar PV array maker [104]. The characteristics have been shown in the following table 6-3.

Table 6-3: Electrical characteristics data of the battery required for the optimization

Battery Rating (Ah)	800
Battery Voltage (volt)	12
Depth of Discharge (D.O.D.)	0.5
Ambient temperature multiplier	1.00

Steps for measuring the battery size:

1. At first daily amp-hour requirement is calculated, dividing watts per day by 12, 24, or 48 depending on the system voltage.
2. Maximum number of consecutive cloudy weather days expected in the projected area is considered. Generally at the time of calculation it is taken as 3-5 days.
3. Then multiplication of the amp-hour requirement with the number of days is done. This is the amount of amp-hours the system will need to store.

4. After that the depth of discharge for the battery is entered. This provides a safety factor so that over-discharging of the battery bank can avoided. The number should not exceed 0.8. Generally 50% depth of discharge that means 0.5 is taken.
5. Then line 3 should be divided by line 4.
6. The multiplier for the average winter time ambient temperature of the battery bank is selected.
7. Then multiplication of line 5 and 6. This calculation ensures that the battery bank will have enough capacity to overcome cold weather effects. The number represents the total battery capacity that is needed by the system.
8. The amp-hour rating of the chosen battery has to be entered then.
9. The total battery capacity of line 7 has to be divided by the battery amp-hour rating of line 8 and round off to the next highest number. This is the number of batteries wired in parallel.
10. Then nominal system voltage has to be divided by battery voltage and round off to the next highest number. This is the number of batteries wired in series.
11. Then multiplication of line 9 with line 10. This is the exact number of batteries required in the system.

6.4.1.3.2. Batteries Charging and Discharging Condition

The state of charge of a battery is fully dependent on the state of charge of a given hour along with the state of charge of the previous hour and also the production and consumption has been calculated from time (t-1) to t. During the charging process, when the total amount of energy from PV and Wind Turbines exceeds the load demand, the available battery bank capacity at hour t can be described by (Bogdan *et al.*, 1996; Bin et al., 2003) [21]:

$$C_{bat}(t) = C_{bat}(t-1)(1-\sigma) + \left(E_{PV}(t) + E_{WG}(t) - \frac{E_L(t)}{n_{inv}}\right) n_{batt} \quad (6.24)$$

On the other hand, when the load demand is greater than the available energy generated, the battery bank is in discharging state. Therefore, the available battery bank capacity at hour t can be expressed as:

$$C_{bat}(t) = C_{bat}(t-1)(1-\sigma) - \left(\frac{E_L(t)}{n_{inv}} - \left(E_{PV}(t) + E_{WG}(t)\right)\right) \quad (6.25)$$

Where $C_{bat}(t)$ and $C_{bat}(t-1)$ are the available battery bank capacity (Wh) at hour t and t-1, respectively; n_{batt} is the battery efficiency (during discharging process, the battery discharging efficiency was set equal to 1 and during charging, the efficiency is 0.65 to 0.85 depending on the charging current) (Bin *et al.*, 2003).

σ is self-discharge rate of the battery bank. Generally the manufacturer documentation gives a self discharge of 25 % over six months for a storage temperature of 20 °C, that is to say 0.14 % per day (Markvart *et al.*, 2003). In the proposed hybrid system the σ is self-discharge rate of the battery bank has been taken as 0.0014.

$E_{PV}(t)$ and $E_{WG}(t)$ are the energy generated by PV and wind generators, respectively; $E_L(t)$ is the load demand at hour t and n_{inv} is the inverter efficiency (generally it is considered as constant from 90% to 92%). In the proposed hybrid system the inverter efficiency has been taken as 0.92.

At any hour instance, the storage capacity of the battery is always stays within the following constraints:

$$c_{batmin} \leq c \leq c_{batmax} \quad (6.26)$$

Where C_{batmax} and C_{batmin} are the maximum and minimum allowable storage capacity. Using for C_{batmax} the storage nominal capacity, C_{batn} then:

$$c_{batmin} = DOD.C_{batn} \quad (6.27)$$

Where, DOD (%) represents the maximum permissible depth of battery discharge.

The continuous variation of the charging or discharging power of the battery is shown in the figure 6-7. As the charging power of the battery is dependent on the power output of the solar PV

and wind turbine, so this charging power changes according to the variation of the generated output power from solar PV and wind turbine. After meeting the load demands if there is any surplus power in the system still remains that can charge the battery bank. At the time of deficit of generated power in the hybrid system, the batteries become discharged and supply its storage power to the system.

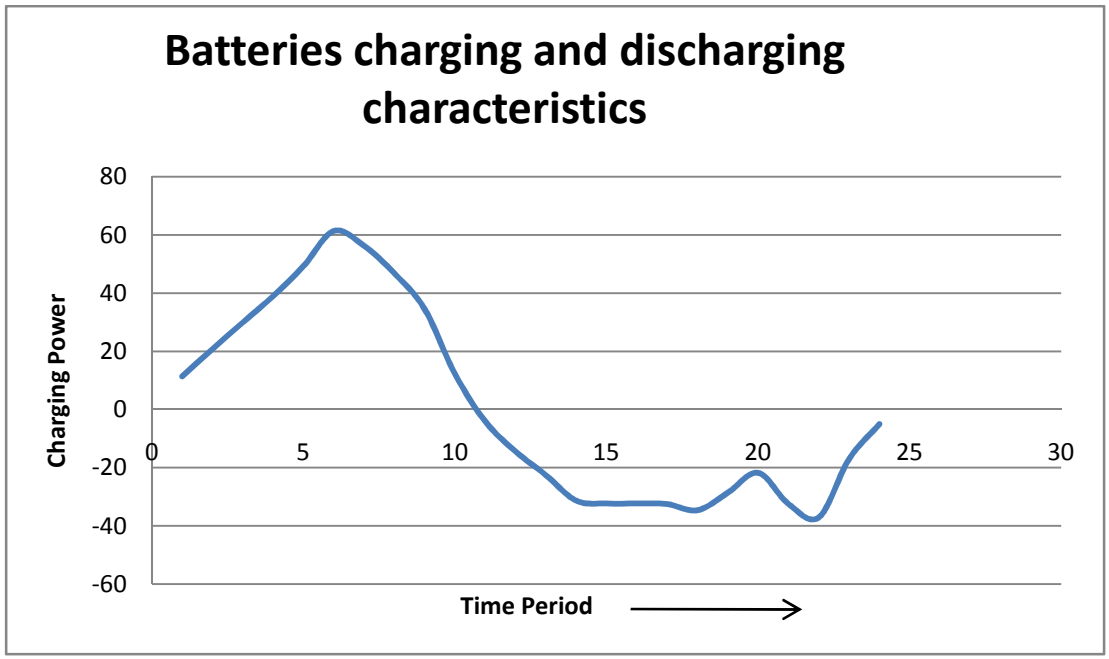

Fig. 6-7: Batteries charging and discharging characteristics

6.4.1.4. Diesel Generator

A diesel generator is considered as a basis of conventional source to generate the electrical power. It gives the AC power to the system. So, for the standalone hybrid system it is directly connected to the AC link. It also helps to maintain continuity and reliability of the system. When there is not enough stored power in the system but still system has a required demand of load in that case Diesel Generator works. That means when battery fails to deliver power to the system DG starts working to meet the load demand.

The fuel consumption of DG unit is related with the rated power. Therefore, DG should not be operated under its minimum point. Usually, manufacturers of the DG give the technical specifications about their products as well as suggestion for a better operational technique. In order to reach the maximum efficiency of operation, the unit should be operated within rated

power and specified minimum value. The environmental issue is a great concern and it is one of the reasons to go for standalone hybrid power system in the field of power generation. A single unit of DG system even placed in a remote rural area may contribute significant amount of carbon dioxide to the atmosphere.

It is assumed in this model that the fuel curve is a straight line with a y-intercept and uses the following equation for the generator's fuel consumption

$$F = F_0 Y_{gen} + F_1 P_{gen} \quad (6.28)$$

Where, F_0 is the fuel curve intercept coefficient, F_1 is the fuel curve slope, Y_{gen} the rated capacity of the generator (kW), and P_{gen} the electrical output of the generator (kW). The unit of F is liters/hour (L/h) and for F_0, F_1L/h. kW. Taking all the data it has been found that the diesel generating is consuming 2.75 liters fuel per hour.

In the proposed hybrid system a 20 KW diesel Generator has been taken as a reference. The power output from the diesel generator is shown in figure 6-8. It is known that in the propose hybrid system the main sources of power are the solar PV and wind turbine. If the load is still required then the batteries has been discharged and supply its stored power to the system. When the battery is also unable to supply power to the system due the unavailability of storage power, at that time Diesel Generator works. Being a conventional source of energy this generator can emit carbon dioxide to the atmosphere and cause air pollution. The amount of emission will also be calculated from the study later through our optimization technique.

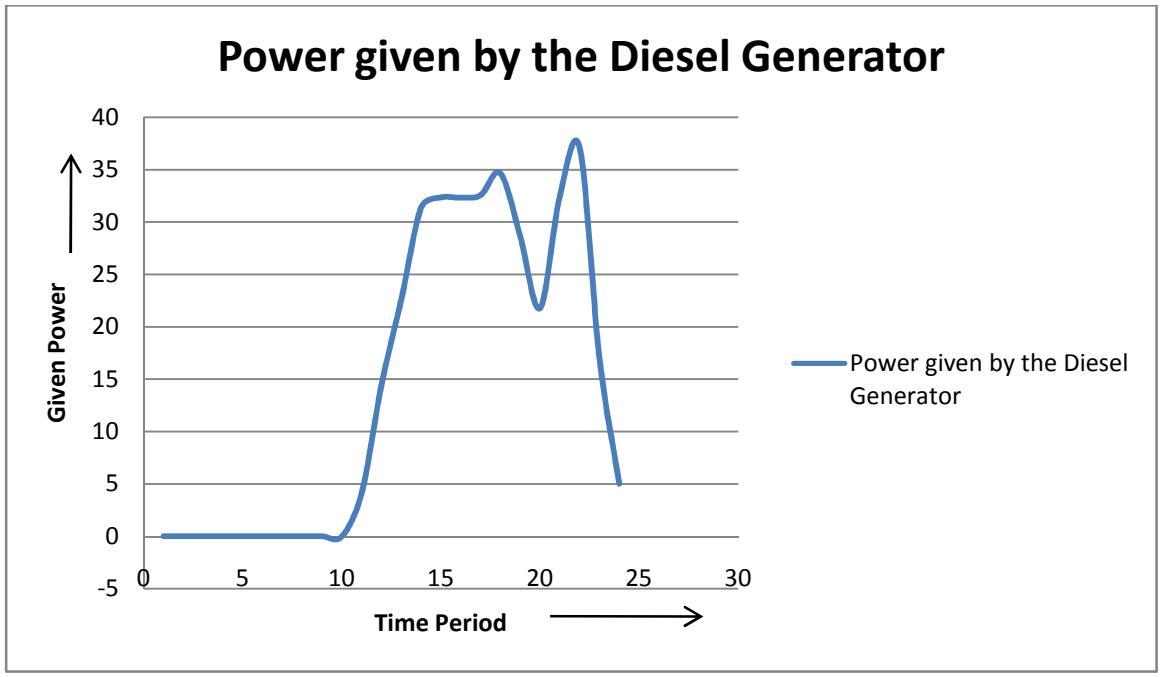

Fig. 6-8: Power given to the hybrid system by Diesel generator

6.5. Load Profile

In the region of Sundarban Island the daily load requirement is considerably not very high. The people of that area lead their life mainly depending on agriculture and business and they are not economically well balanced. So they do not require larger amount of electricity. In the test location of Laxmijanardanpur village there are 753 households, consists of 6 persons average in a house. A brief case study has been done regarding to their socio-economic set up. From that study, a 24 hours load demand profile has been made. The profile of 24 hours daily load requirement of the test location is shown in figure 6-9. Most of the appliances used in the test location are operating with AC-powers and thus AC-loads are considered here. The variation of load requirement from hour to hour is well directed in the graph.

The load profile shows the peak demand appears during night time from (9-10) p.m. It explicitly accounts for the residential loads like in most rural areas, where power is consumed for lighting and other related activities. Demand can be of different types like peak demands, average demands, base demands, daily energy demands and average daily demands. At which hour the load required is in peak are also shown in the graph. Depending upon the requirement of load

demand the sizing of the proposed system components, the output power given to the system for each component, and different cost parameters can be analyzed.

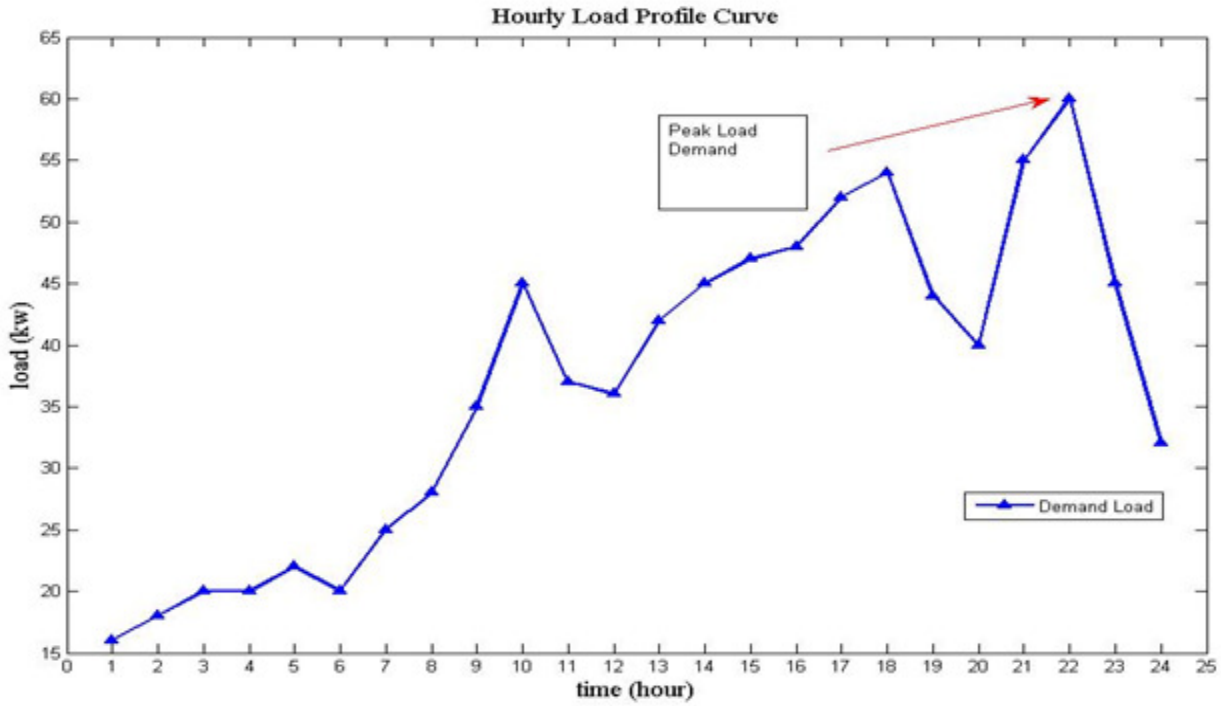

Fig. 6-9: Load demand with respect to different hours of a day

The comparison between the demand power and the solar PV plus wind turbine output power of 24 hours of a day is shown in the figure 6-10. By this comparison it can be easily understood that in every hour how much excess or deficit energy are there in the system. If there is excess energy, it will help in charging the batteries and in reverse case the battery will be discharged or otherwise the DG will deliver the power. The x-axis represents the time period of a day and the y-axis denotes the load demand (blue lines) as well the wind plus solar output power (red lines).

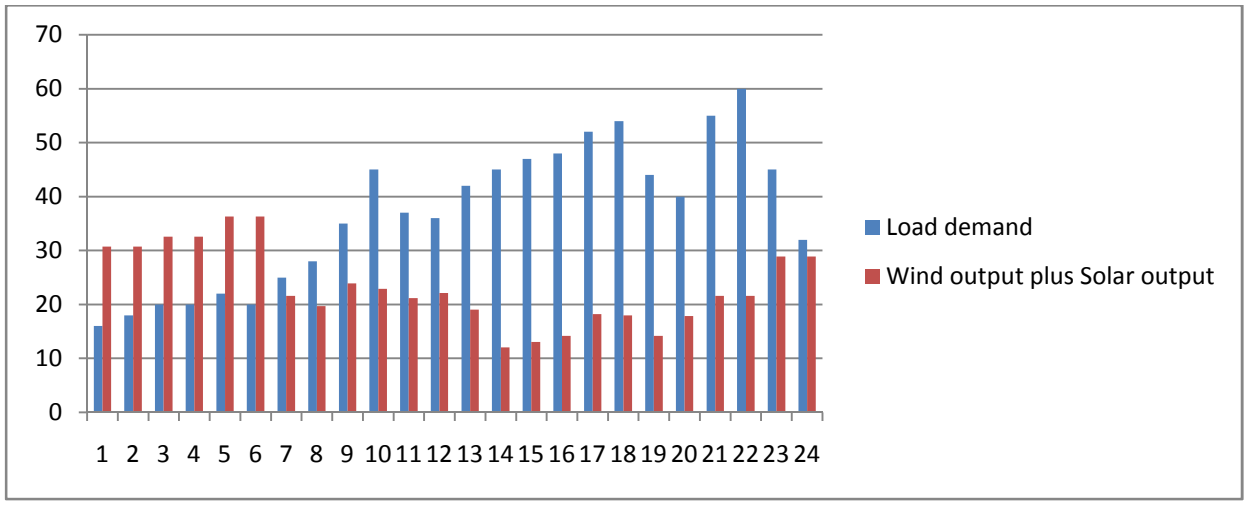

Fig. 6-10: Comparison between the load demand and wind plus solar output power

6.6. Cost and Cost Parameters

Power generation from any plant or sources is associated with cost and some costs are fixed and some are variable. For calculating the unit energy cost or cost of energy of each plant few basic parameters of that particular plant should be known. The associated cost parameters with any plant are as follows:

a) <u>Annualized fixed cost:</u> This cost is threefold in nature. Annualized Capital cost, Annualized Replacement Cost and Annual operation & Maintenance Cost.

b) <u>Annualized Variable cost:</u> This is basically the cost of fuel or fuel cost.

<u>The basic Equations:</u>

If I be the rate of interest and N is Lifetime of the project i.e. if the loan is taken for capital investment and replacement cost of a component for the period of project lifetime then,

Capital Recovery Factor = $CRF = \frac{I(1+I)^N}{(1+I)^N-1}$ (6.28)

If the total capital investment for a component = $Ccap$

Then, Annualized Capital Cost = $ACP = Ccap * CRF$ (6.29)

And, Annualized Replacement Cost of a component:

$$ARC = Replacement\ Cost \times f \times \frac{I}{\{(1+I)^{N_{Comp}} - 1\}} - Replacement\ Cost \times \frac{\left[N_{Comp}\left\{1 + FLOOR\left(\frac{N}{N_{Comp}}\right)\right\} - N\right]}{N} \times \frac{I}{\{(1+I)^{N} - 1\}}$$

Where, $f = \frac{[I(1+I)^N / [(1+I)^N - 1]]}{[I(1+I)^M / [(1+I)^M - 1]]}$ (6.30)

Where, M = $N_{Comp} \times FLOOR\left(\frac{N}{N_{Comp}}\right)$

Annual Maintenance Cost = AMC

Then the total annualized fixed cost = annualized capital cost + annualized replacement cost + annualized operation & maintenance cost

And if Annual Fuel Cost = AFC

Then, total annual cost of a component = annualized capital cost + annualized replacement cost + annualized operation & maintenance cost + Annual Fuel Cost.

The system performance is evaluated in respect to the Generation Cost (GC) i.e. the cost incurred to generate the power to meet the load as well as Cost of Energy (COE) which is the cost the customers need to bear for using unit amount of energy from the system. The program for this proposed system optimizes the system configurations according to Net Present Cost (NPC) rather than cost of energy.

Cost of unit energy (COE) = Σ(Total Annual Cost of each component) / Total Energy Catered by the system

Cost of generation (GC) = Σ(Total Annual Cost of each component) / Total Energy generated by the system

Net Present Cost (NPC) = Σ(Total Annual Cost of each component) / Σ (Total CRF of each component)

6.7. Optimization Procedure

In this study, the required necessary inputs for the system optimization are the Capital costs, Replacement costs, Operation and maintenance costs of all components, the inflation rate, the efficiency lifetime of all the components and lifetime of the project, specifications of all the components, hourly load demand of the proposed site and the hourly meteorological data. The electrical specifications of the different components of the hybrid system, the hourly load demand of the test location and the hourly meteorological data of the different renewable energy has been discussed already in the previous section. The following table shows the total cost parameters of each and every component and the other data that are required to optimize the system's net present cost and cost of energy of the proposed hybrid system.

Table 6-4: Cost optimization parameters

Nominal Interest Rate (%)	6
Project lifetime	25
PV panel lifetime	25
Wind Turbine lifetime	20
Battery banks lifetime	10
Inverter lifetime	25
Capital cost of PV Panel (rupees)	1820610
Capital cost of Wind Turbine (rupees)	1125000
Capital cost of Battery Banks (rupees)	50400
Capital cost of Diesel Generator (rupees)	190000
Capital cost of Inverter (rupees)	654993

O & M cost of PV Panel (rupees)	18206
O & M cost of Wind Turbine (rupees)	112500
O & M cost of Battery Banks (rupees)	5040
O & M cost of Diesel Generator (rupees)	19000
O & M cost of Inverter (rupees)	6549
Replacement cost of Wind Turbine (rupees)	1012500
Replacement cost of Battery Banks (rupees)	45360
Replacement cost of Diesel Generator (rupees)	171000
Fuel cost (rupees/lt.)	43.74

6.7.1. System Optimization with the help of PSO

The first step is the initialization of the first population of particles, the initial position as well as its initial velocity of particle consists of four random vectors x_1, x_2, x_3, x_4 for position and v_1, v_2, v_3, v_4 for velocity. All procedures are applied for all particles in the population. Here, the value of x_1, x_2, x_3, x_4 as representation of the size of PV panels, Wind Turbines, battery banks and the rated capacity of DG unit respectively. After initialization of the first population is completed, the target of simulation as depicted in the flow chart is established to determine the Net Present Cost, Cost of Energy, Annual fuel consumption of DG unit, Carbon dioxide emission. The PSO calculates the NPC and COE as the objective function and choose one of the particles which have a smaller objective function as the best position of particle and the best position of the group. The next position and velocity are determined according to the equations of PSO.

In every iteration, the objective function is calculated for each particle and compared with the previous values. The best position of each particle is evaluated and the best position of the group is determined by comparing the best positions of the particles. Using PSO's equation, the next velocity and position are calculated after iteration reaches the maximum iteration. In this stage,

the best value of the group becomes the optimum solution of the problem. PSO attempts to find the optimal size and scheduling of the system economically as possible without any electricity shortage conditions.

6.7.2. Methodology

PSO based mat lab m-file code has been developed to determine the optimal configuration of Solar PV-Wind Turbine-Battery-Diesel system in Laxmijanardanpur village, Pathar Pratima block, Sundarban region, West Bengal (India). The optimization was done with the help of a personal computer with the specification are Intel Core2 with the processor speed is 3GHz and 2GB of RAM. The daily load profiles are represented by a sequence of powers which is constant over a step time of one hour. The solar radiation and wind speed in Laxmijanardanpur village has been discussed earlier. Meanwhile, another data set regarding to the cost parameters used for the optimization are shown in the previous table. In this simulation, PSO parameters consist of five vectors which represent the size of Wind Turbines, Solar PV arrays, Battery banks, Diesel Generators and Inverter. The values of C, C_1 and C_2 are 1, 1.496, 1.496 respectively. The PSO can be classified into different types. In this work Stochastic Inertia Weight PSO has been used for the optimization. The convergence curves of the PSO algorithm for several independent runs are depicted here.

It can be seen that the optimal values are obtained about 10-15 iterations. Hence, 100 iterations can be considered as a fair termination criterion. Moreover, it can be observed that the optimal value for all the runs almost converges to the same optimal value (global optimum). Optimization using PSO is very much faster than the other optimization process. The optimized scheduling and sizing result for the system under study has been shown in the next chapter. From the scheduling table the output from several components has been found according to every hour of a day. From the sizing analysis the best optimum combination can be found using which the net present cost of the system and cost of energy will be less. The emission of carbon-dioxide for a single day, for one year and for per unit (kWh) generation from the proposed hybrid system have been calculated. Next, the flow chart of the proposed system shows how the system has been optimized with the help of Particle Swarm Optimization technique to find out the optimized objective functions.

6.7.3. Flow Chart

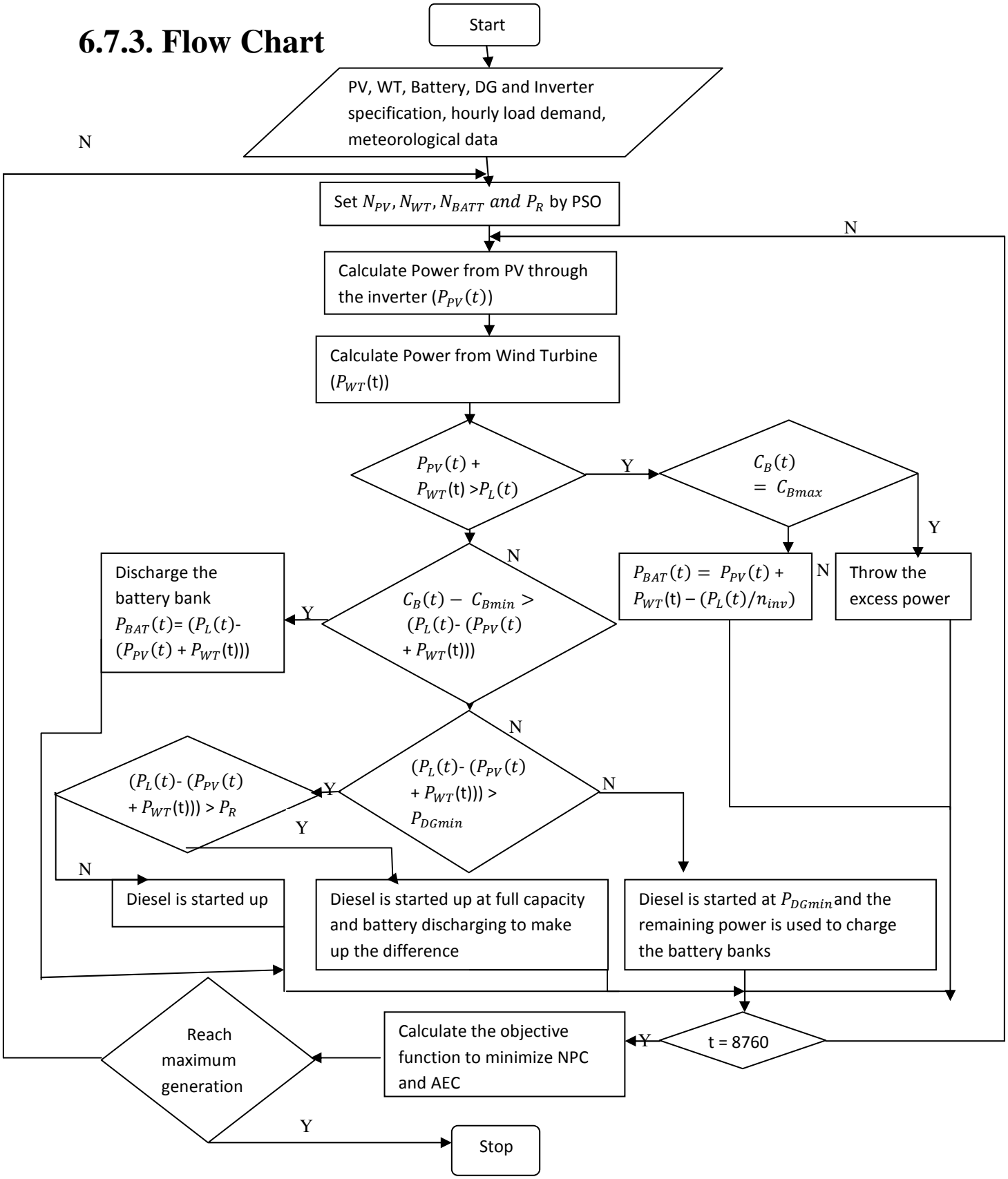

Fig. 6-11: Flow chart of optimization procedure with PSO

Chapter 7: Results and Discussion

7.1. Application and Results

In the previous chapter a system comprises of several renewable or conventional sources (DG as back-up) has been formulated. With the help of PSO algorithm the system has been optimized to minimize the system's Net Present Cost and Cost of Energy and to find out the emission from the system for a single day, for one year, for unit (kWh) generation and also calculate the fuel consumption per year by the Diesel Generator. From the study it has been known that hybrid combination of PV-Wind-Battery-Diesel system has greater reliability for electricity production In addition, the integration of PV and Wind system with battery storage and diesel unit as a back-up provides a reduction in the operational costs and emitted air pollutants to the atmosphere.

7.2. Optimized Scheduling of Hybrid System

From the following table of the optimal scheduling, all the profile related to the power generation output, excess and deficit power output, battery charging power can be found for the proposed hybrid system. This will give a specific idea about the proposed system parameters and its different characteristics features. This scheduling is the base to find the proper sizing of this proposed system. Depending on different data like load demand of the Laxmijanardanpur village (test location), meteorological data like solar radiation and wind speed, several features and ratings of each and every component of the system; the optimized table has been made. Above the meta-heuristic computing process "Particle Swarm Optimization" has taken a huge part to get the optimized scheduling of the system. The first column of the table represents the 24 hours load profile of a day. After that the output from different components, then the excess and deficit energy of the system and next the energy that can charge the battery has been distributed in the column respectively.

Table 7-1: For Optimized scheduling of 24 hours of a day

Load Profile (KW)	Wind Turbine Output (KW)	Solar PV array Output (KW)	Excess/Deficit Power (KW)	Battery Charging Power (KW)
16.0000	30.7259	0	14.7259	11.3344
18.0000	30.7259	0	12.7259	20.7549
20.0000	32.5822	0	12.5822	29.8505
20.0000	32.5822	0	12.5822	38.8931
22.0000	36.2947	0	14.2947	49.1907
20.0000	36.2947	0	16.2947	61.2761
25.0000	21.5772	0	-3.4228	56.1617
28.0000	19.7210	0	-8.2790	46.7276
35.0000	17.8647	6.0296	-11.1057	34.4284
45.0000	16.0085	6.8878	-22.1037	12.1134
37.0000	14.1522	7.0302	-15.8175	-4.1369
36.0000	14.1522	7.9667	-13.8811	-14.4598
42.0000	10.4397	8.6218	-22.9385	-22.6021
45.0000	3.1473	8.8806	-32.9721	-31.3524
47.0000	3.1473	9.8973	-33.9554	-32.3360
48.0000	6.8598	7.3001	-33.8401	-32.3119
52.0000	12.2960	5.9323	-33.7717	-32.5494

54.0000	14.1522	3.7942	-36.0536	-34.6368
44.0000	14.1522	0	-29.8478	-28.6228
40.0000	17.8647	0	-22.1353	-21.7715
55.0000	21.5772	0	-33.4228	-32.4746
60.0000	21.5772	0	-38.4228	-37.0941
45.0000	28.8697	0	-16.1303	-17.0369
32.0000	28.8697	0	-3.1303	-5.0260

From the previous table it can be found that the generated power from different components of the proposed hybrid system has been recycled continuously into the system. Every column is described below.

- 1st column- 24 hours variable load profile of the village. Load demand is less at the time of night hours from (12 - 4) a.m. and demand is more especially at the noon time or at the evening. The maximum demand, experienced by the system is 60 KW in between (21–22) p.m.
- 2nd column- 24 hours Wind Turbine output. A steady output is coming according to a steady wind speed. But within (12-14) p.m. hours the output gets very low and in between (4 - 6) a.m. it is very high at around 36.2947 KW.
- 3rd column- 24 hours Solar PV Arrays output. It is a very non-reliable source of energy. Only 10 hours a day the PV can deliver energy output in accordance with the proper sunlight. Otherwise, the output becomes zero for the rest of the day.
- 4th column- 24 hours excess or deficit energy of the system. That means, for a particular hour, after getting the energy from the wind and solar if their summation of energy is more than the demand of that hour then there will be excess energy and if the summation is less than the demand then the term deficit will come.
- 5th column- The energy that batteries are getting for continue their charging process and the discharged energy from the batteries. The excess energy can charge the battery

following the proper charging equation described earlier. And when there is shortage in demand, battery becomes discharged.

7.3. Optimized Sizing of Hybrid System

In the system there are some objectives that are to be optimized at last. So after using Particle Swarm Optimization technique a proper combination of the hybrid components has been found by which the system can be well optimized. The combination in which the system requires least Net Present Cost or the Cost of Energy is the optimized sizing of the propose system. From this result, the numbers of each component that is connected in this hybrid system and responsible for giving the optimized results has been shown.

Table 7-2: For Optimized sizing of the system

System components	Sizing of the system
Wind Turbine	5
Solar PV Array	2
Battery	10
Diesel Generator	2
Inverter	1

The sizing of the different system components has shown here. The number of Wind Turbines required in the system is five. Each of the turbines is of 15 KW. Then the Solar PV Array's size is two. In each array there are 60 solar module of 150W. Because each of the array that has been taken as reference for this system is of 9 KW which consists of 150 KW solar modules. So, in this proposed system the number of solar modules or solar panels required is (60 x 2) 120.The requirement of 800Ah, 12V DC battery in the system is ten. These batteries are used as energy storage class device. The optimized result of Diesel Generator, which is used to maintain the reliability of the system during the unbalanced condition, is two. Each of the generators is of 20

KW. The number of Inverter, which is used to convert the DC power output of the system in our required AC power, is one which is of 9 KVA.

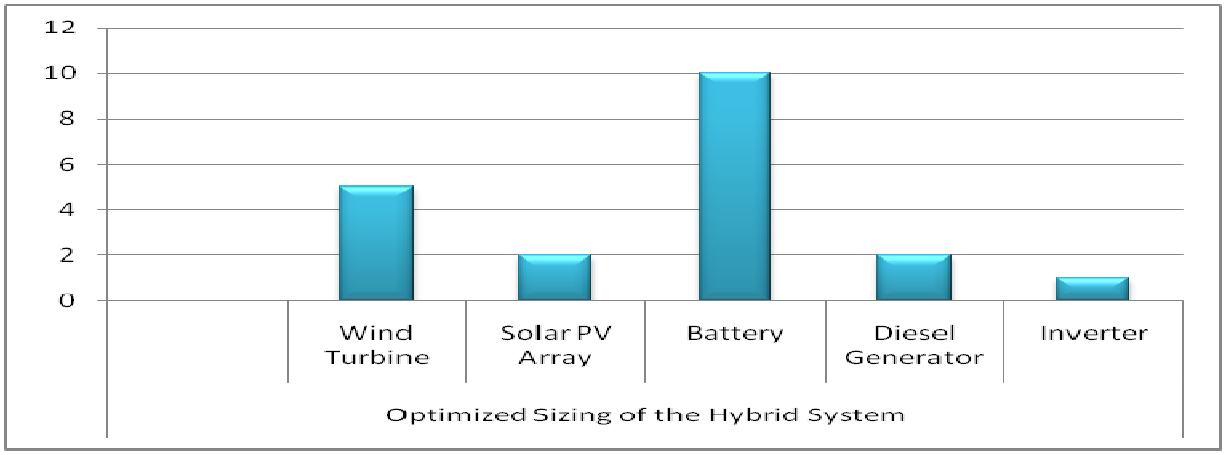

Fig. 7-1: Optimized sizing results of the proposed hybrid system

7.4. Optimized results

The main objectives of our system are to minimize the Net Present Cost and Cost of Energy of the system to make the system economically viable and to reduce the Carbon dioxide gases from our system and make our system more eco-friendly. Also by calculating the annual fuel consumption of the system an idea can be found for the long term process that, for the total lifetime of the system how much fuel can be burn by the system and how much emission can be possible. Accordingly, some ideas related to the adverse atmospheric pollution effect, that is totally dependent on this emission, can also be found.

Table 7-3: Optimized results

Objective Functions	Results
Net Present Cost (Rupees)	8879700
Cost of Energy (Rupees/kWh)	8.927
Emission of Carbon dioxide per day (kg.)	103.1800

Emission of Carbon dioxide per year (Tons)	37.6607
Emission of Carbon dioxide per unit generation (kWh)	0.116
Fuel consumption per year (Litres)	14053

7.5. Comparison Respect to Emission

From the above optimized objective function, Net Present Cost and the Cost of Energy of the proposed hybrid system have been found. From the emission point of view, several data have also been found. They are emission of carbon dioxide from the system for one day, one year and also for unit (kWh) generation of power. The amount of carbon dioxide that is emitting for per unit generation in this proposed system can be compared with a thermal power plant. In a coal based 60 MW thermal power plant, the average amount of carbon dioxide emits for per unit (kWh) generation is 0.804 kg [103]. For this test system, the average amount of carbon dioxide that is emitting for per unit generation (kWh) due to the fuel consumption by the DG is 0.116 kg. So, it can be said that in compare to a 60 MW coal based thermal power plant, this proposed system is much more reliable from emission point of view. So, a combination of Solar PV-Wind Turbine-Battery-DG hybrid system can reduce the adverse atmospheric air pollution effect in compare to a coal based thermal power plant.

7.6. Optimized Graph

In the optimized figure the minimum Net Present Cost and the average mean cost of the system are shown. 100 iterations have been taken and the system has become optimized within 10-15 iterations. The figure also shows the converging characteristics of the minimum and mean cost. In the X-axis iterations are plotted and in the Y-axis the minimum and mean cost. The blue line of the figure indicates the minimum cost and the green line indicates the mean cost. At first the blue line that means the minimum net present costs has been optimized. After that the green line that means the average costs has been converged over the minimum cost.

Figures for the Optimized Cost Results:

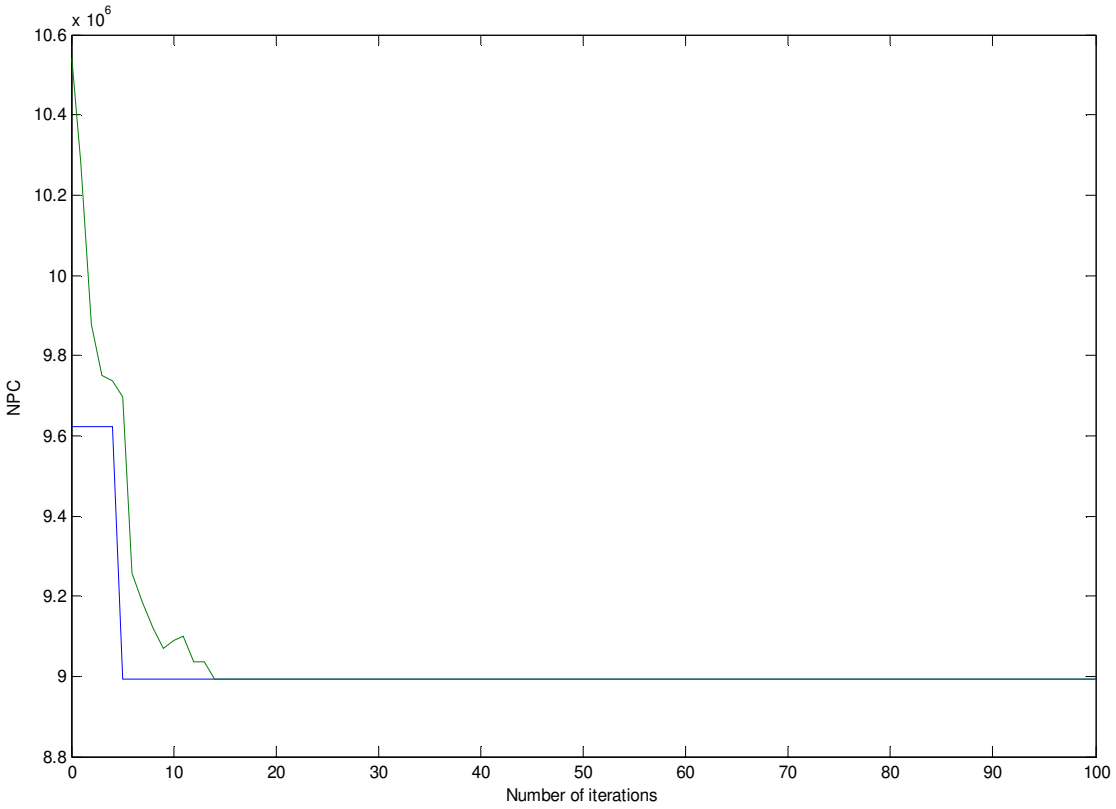

Fig. 7-2: Optimized Graph by Particle Swarm Optimization Technique

During 7-8 iterations the system are getting optimized. After that the system gets the stability. That means the straight line shows the ultimate optimal cost results of the system. This optimal result proves that using this optimized combination of hybrid components, the cost cannot be less than our optimized cost.

From the objective related to emission point of view it can be seen that combinations of different renewable sources in a system are reducing the chances or quantities of emission. Our main aim was to decrease the emission rate of Carbon dioxide and make our environment green. So, the amount of emitted Carbon dioxide from the system has been found out. The main emissions occurred obviously from the Diesel Generator which has been found. Apart from that also some emissions are caused by the other sources indirectly like at the time of Solar PV or Wind Turbine installation etc. The Carbon dioxide emitted from that components are 0.017 Kg, 0.23 Kg and

0.85 Kg per kWh for the Wind Turbine, Solar PV and Battery respectively [99]. For this system, the carbon dioxide emission for one day is 103.1800 kg and for one year is 37.6607 tons and 0.116 kg for per unit (kWh) generation. This can cause a huge adverse air pollution effect to the atmosphere.

Chapter 8: Conclusion and Future Aspect

8.1. Conclusion

For the crucial problem of energy supply in remote villages such as Laxmijanardanpur of Sundarban regions, the above described system is the most viable option. Even though the initial investment required is comparatively high, the NPC or COE analysis shows that for a remote region the standalone hybrid energy system can be much cost-effective in compare to the conventional grid connection supply. The electricity that can be found from the grid supply can be cheap but the grid extension cost and transportation and distribution cost results the increment of unit cost of energy, especially where the grid has to be extended over a considerable distance. Above all, once a hybrid system has been installed it's operating and maintenance cost becomes very low. For these above reasons, a stand-alone hybrid system can be the most financially efficient and reliable for this kind of study.

In this study, the assessment of various resources and the calculation of load demand have been carried out and the NPC and COE have been found out through the optimized result for the specified system configuration. A combination of Solar PV, Wind Turbine, DG and batteries has been identified as the cheapest and most dependable solution with a NPC of 8879700 rupees and COE of 8.927 rupees/KWh. The study shows that the proper combination of different RETs can be very reliable for the rural electrification of the remote villages. The result of emitted Carbon dioxide from the system for per day, one year and for unit generation of power has been done. The amount of emission of carbon dioxide for per unit (kWh) generation of power has been calculated for the proposed system and compared to a 60 MW coal based thermal. It has been found from this comparison that this proposed system is emitting much less carbon dioxide for per unit generation than the thermal power plant. It proves that the combination of different RETs with the Diesel Generator can cause less emission than the conventional energy sources.

All in all, PSO has proved a valuable optimization technique and MATLAB as an important tool in this study especially because of its ability to simulate numerous components and load combinations. The graphs created by MATLAB through PSO make the simulation's results clear and easy to understand. One drawback of PSO, however, is that its optimization process is based on identifying the cheapest technology. This, however, requires the system designer to specify the exact costs of different components etc., which might not always be possible.

8.2. Further Recommendations

There is a considerable good market for stand-alone RETs both in rural regions and also in highly populated areas. To meet this market's demands, policies should have to be implemented to promote RETs and address the problems still connected with them, such as lack of a sufficient operation and maintenance (O&M) infrastructure, the need for more awareness of RETs, market based delivery models and finally the high investment costs.

Accordingly, the major areas for further investigation are:

- Village load, RES and related costs data with efficiency and accuracy.
- Barriers faced by small scale RETs to become sustainable.
- Developing public-private partnerships.
- Role of RETs to solve energy crisis and improve rural development.
- Effect of RETs in reducing the emission level.
- Taking the possibility of stand-alone hybrid RET systems into account in grid expansion plans.

Off-grid electricity generation based on hybrid RET systems plays a pivotal role in addressing the issue of a country's energy security and policies encouraging further initiatives towards this motion should be implemented. Especially local governments can play an important role in promoting RETs. These can be taken into account in their decision making, planning and in connection with the municipal infrastructure. This way, the governments will also set an example for businesses and citizens.

Accordingly further work is recommended in: -

- Promotion of RETs by several policies at state and local level.
- Promotion of RETs with the help of financial set-up.
- Creating local infrastructure for the installation, O&M of RET systems.
- Policies to make more emission less model.

Chapter 9: References

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