OPTIMAL PLANNING OF INTEGRATED RENEWABLE ENERGY SYSTEMS

Ph.D. THESIS

by

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ABSTRACT

Energy is the vital input for the sustainable development of a nation. With the rising population, the demand has increased manifold. This rising energy demand led to the evolution of some new and alternative energy resources. Unlike conventional resources, these resources are not only renewable but also environment friendly. These renewable energy resources include solar, wind, hydro and biomass. As far as solar and wind are concerned, they are omnipresent. Despite having several advantages, these resources have certain limitations which constrained their dissemination. Their utilization in an integrated manner complements each other and the individual short coming can be overcome. This led to the development of integrated renewable energy systems (IRES).

Integrated renewable energy systems are the systems comprising two or more renewable energy resources supplying different energy needs in tandem. The intermittent nature of renewable energy resources like solar and wind can be overcome in these systems. With the increase in the reliability of the system, the cost of the system also increases. This led the researchers to focus on developing an optimum trade-off between the reliability and the cost of the system. In addition to the increase in reliability, the major advantage of these systems is the availability of resources even at the farthest and remotest site. The supply of energy to these sites otherwise would either be not possible or economically not viable. That’s why, the development of IRES would result in the development of remote rural areas by supplying energy.

India, being a developing country, has its own limitations of supplying energy to rural areas. There are still a large number of villages deprived of clean sources of energy even for cooking. Cooking sector is considered as one of the major energy consuming sector in developing countries. In addition to cooking, provision of electricity to rural areas is still a difficult task. This is mainly because of low consumption due to disperse population. The high capital investment and low return because of low consumption make the system economically infeasible. Here, comes the role of locally available renewable energy resources.

Different combinations of resources as integrated renewable energy system have been reported in the literature. These combinations include solar, wind, hydro and biomass energy resources. In context of Indian rural energy scenario, the three most widely available energy resources are solar, wind and biomass energy resources.

The solar and wind energy resources are considered to be the most complex resources as far as their mathematical modeling is concerned. Various mathematical models have been found in the literature.The mathematical models discussed in the literature were, in general, based on either deterministic approach or probabilistic approach. The deterministic approach, being the most common approach, works on considering the average value of the quantity in a given time segment. The limitation with this approach is that this approach is not applicable for time-ahead prediction problems. The probabilistic approach, another mathematical approach found in literature, is based on the representation of the data by a suitable probability density function and thereby estimating the probability of the state in which the data lies.Besides, techniques based on statistical and non-statistical approaches are also found in literature. These techniques, basically, are used for the development of time series models. Nowadays, the development of time series model for solar and wind energy resources has substantial scope in these types of systems.

To develop a time series model, it is important to have a series of historical data of solar radiation and wind speed. The continuous data recording, in Indian context particularly for rural areas, is a tedious task. The time series model based on classical regression techniques is highly dependent of data series. The limited availability of solar and wind energy resources' data restrict the scope of classical statistical regression techniques and presents a good opportunity for the application of non-statistical techniques in this area.

The application of artificial intelligence, particularly artificial neural network, is still new to the renewable energy system domain. The non-statistical techniques based on artificial neural network are emerging as the good techniques for solar and wind energy modeling to overcome the data availability constraints. Exploration of neural networks for the development of time series models may be considered for further study.

Most of the work reported in the planning of IRES was focused on the sizing of resources. As far as planning of integrated system is concerned, besides sizing, the operational strategy plays an important role in analyzing the economics of the system. This left a substantial scope for the development of time-ahead operational strategy with the application of time series modeling of solar and wind energy resources.

As far as optimization techniques are concerned, various optimization techniques were reported in the literature. Classical techniques have limitations of search area and initial value definition. In the similar manner, evolutionary based algorithms have limitations of excess time and complexity. These limitations led to the emergence of hybrid techniques. Different hybrid techniques have been discussed in the literature. The application of these techniques was limited to sizing problems. This opened up a good amount of scope for hybrid techniques for the optimal planning of integrated renewable energy systems.

In this study, a rural remote site has been considered and an integrated system has been developed for supplying different demands of rural area. The considered site is a small village, named *Tapri*, with a population of 800 persons in the Kinnaur district of Himachal Pradesh, India. The main occupation of the natives is apple farming. The rural energy demands considered for the site arethermal energy for cooking, electrical energy for lighting and other uses and mechanical energy for water pumping. These demands have been estimated for the site through primary as well as secondary data collection. The thermal demands mainly comprises of cooking twice a day. The electrical demands include residential as well as common area lighting and other commercial activities. The mechanical demands include water pumping requirements for the apple farming. To estimate the demand, the entire year has been divided into four seasons, that are, December to February as season I, March to May as season II, June to August as season III and September to November as season IV.

The resource assessment is another important aspect of the problem. The solar radiations and wind speeds have been predicted using ANN based techniques. Different networks and training algorithms have been reviewed with the input and output parameters considered. Radial basis function network is then used to predict the solar radiations and wind speeds. The developed model for wind speed and solar radiations is then validated through their regression coefficient values (R-values) and root mean square error values. The R-values of solar radiations for season I-IV are found as 0.93, 0.96, 0.96 and 0.93 respectively. Similarly, the R-values of wind speeds for season I-IV arefound as 0.88, 0.84, 0.98 and 0.86respectively. The obtained models are then applied to determine the solar radiation and wind speed values in a day ahead scenario.

The next step, after the determination of resource and load, is to obtain an optimal operational strategy such that the operational cost of the system comes out to be minimum. IRES has been worked out with different load – resource combinations. For this system, the operational strategy problem has been formulated. The objective function includes the cost of operation of different energy conversion facilities and a cost of energy not served is also included in the function. The operation cost includes the cost of generating electrical energy, thermal and mechanical energy from solar, wind and biomass energy resources cost of energy conversion from one form to another form. Various demand balance constraints for thermal, electrical and mechanical demands have been considered along with their upper and lower bounds. Mechanical load is considered as deferrable load and can be supplied at any time segment of the day. Initially, the sizes of different energy conversion facilities are assumed. This is a linear programming optimization problem and there are 266 variables with 23 equality constraints and 52 inequality constraints. The problem has been solved through Optimization Toolbox of MATLAB. The operational strategy for a typical day has been obtained different factors (α_{TL})ratio of thermal energy not served to the total thermal load, (α_{EL}) ratio of electrical energy not served to the total electrical load and (α_{ML}) ratio of mechanical energy not served to total mechanical load are included to check the energy not served for different demands. It was found that value of 0.56kWh of thermal energy gets unserved and 0.63kWh of electrical energy remains unserved for a typical day.

For planning of IRES, it is necessary to work out the optimal sizes along with operational strategy. For optimal planning, the overall cost of the system should be minimum. Hence, the overall cost has been considered in objective function which comprises of capital as well as operational cost. The capital cost is governed by the size of energy conversion facility, while the operation cost is governed by power output at different instant of time. Hence, the developed formation has both the discrete as well as continuous variables. A hybrid EP-LP based approach under MATLAB environment has been proposed to solve the developed formation. A discrete size selection has been made through evolutionary programming (EP) and with the help of these sizes, the operational strategy has been worked out with minimum operational cost using linear programming technique. The fitness function has been evaluated by combining operational cost and capital cost.

Summarizing, the study carried out may be useful for the planning and development of IRES for a remote and unelectrified site. However, this study has wide scope of research in future. The dispatch strategy has theoretically been coined out. There is a scope of realization of proposed operational strategy by designing an adaptive controller. Besides, there is a need for reliability analysis with the inclusion of some storage devices as well as dump load.

NOMENCLATURE

Symbol	**Title**	**Unit**
H	Monthly average daily global solar radiation	kWh/m^2
H_o	Monthly average daily extraterrestrial solar radiation	kWh/m^2
S	Monthly average daily hours of bright sunshine	h
S_o	Monthly average day length	h
I_{sc}	Solar constant	Wm^{-2}
φ	Latitude of the site	Degree
δ	Solar declination	Degree
ω_S	Mean sunrise hour angle for the given month	Degree
D	Number of days of the year	--
INR/Rs.	Indian rupees	--
I_b	Direct solar radiations	kWh/m^2
I_d	Diffused solar radiations	kWh/m^2
R_d	Tilt factors for the diffused part of solar radiations	--
R_r	Tilt factors for the reflected part of solar radiations	--
A_{PV}	Area of panel	m^2
I_T	Total solar radiations	kWh/m^2
P_{PV}	Hourly power output from PV	kW
η	System efficiency	--
η_m	Module efficiency	--
η_r	Module reference efficiency	--

η_{PC}	Power conditioning efficiency	--
P_f	Packing factor	--
β	Array efficiency temperature coefficient	--
T_r	Reference temperature for the cell efficiency	^oC
T_c	Monthly average cell temperature	^oC
T_a	Instantaneous ambient temperature	^oC
NOCT	Normal operating cell temperature	^OC
DE(T)	Energy deficit during the time period T	kWh
L	Total load during the time period T	kW
C_R	Charge recovery of the battery days	--
B_E	Watt-hour efficiency of the battery	--
X	Annual average equivalent peak hours/day	--
ω	Hour angle	Degree
ω_s	Sunset hour angle	Degree
Mfr	Mass flow rate	kg/s
V	Wind speed	m/s
c_i	Center vector	--
R	Regression Coefficient	--
RMSE	Root Mean Square Error	--
A_{ME}	Availability of Mechanical to Electrical Conversion Facility	--
C_{ME}	Operating cost of mechanical to electrical conversion facility	INR
P_{ME}^{i}	Electrical power through mechanical to electrical conversion at ith time segment	kW
A_{ET}	Availability of Electrical to Thermal Conversion Facility	--

C_{ET}	Operating cost of Electrical to Thermal conversion facility	INR
P_{ET}^{i}	Thermal power through electrical to thermal conversion at i^{th} time segment	kW
A_{EM}	Availability of Electrical to Mechanical Conversion Facility	--
C_{EM}	Operating cost of Electrical to Mechanical conversion facility	INR
P_{EM}^{i}	Mechanical power through electrical to mechanical conversion at i^{th} time segment	kW
A_{TM}	Availability of Thermal to Mechanical Conversion Facility	--
C_{TM}	Operating cost of Thermal to Mechanical conversion facility	INR
P_{TM}^{i}	Mechanical power through thermal to mechanical conversion at i^{th} time segment	kW
C_{BM}	Operating cost of biomass to mechanical conversion facility	--
P_{BM}^{i}	Mechanical power through biomass to mechanical conversion at i^{th} time segment	kW
C_{α}	Cost of unserved energy	INR
α_{ML}	Ratio of energy not served to the total mechanical load	--
α_{TL}	Ratio of energy not served to the total thermal load	--
α_{EL}	Ratio of energy not served to the total electrical load	--
v^{i}	Volume of digester at i^{th} time segment	m^3
P_{BT}^{i}	Output from biomass to thermal energy conversion facility in time segment i	kW
CV	Calorific value of biogas	kWh/m^3
η_{BT}	Conversion efficiency of biomass to thermal	--
η_{BM}	Conversion efficiency of biomass to mechanical	--
P_{ST}^{i}	Output from solar thermal energy conversion facility to meet the thermal load during time segment i	kW
P_{TL}^{i}	Total thermal load during the time segment i	kW

P_{SE}^{i}	Contribution from SPV to meet electrical load during time segment i	kW
P_{WE}^{i}	Contribution from wind electrical energy conversion facility to meet electrical laod during time segment i	kW
η_{EM}	Conversion efficiency from electrical to mechanical	kW
η_{ET}	Conversion efficiency from electrical to thermal	--
P_{EL}^{i}	Total electrical load during time segment i	kW
η_{ME}	Conversion efficiency from mechanical to electrical	--
P_{ML}^{i}	Total mechanical load during time segment i	kW
ENS_{TL}	Thermal energy not served	kW
ENS_{ML}	Mechanical energy not served	kW
ENS_{EL}	Electrical energy not served	kW
P_{SPV}^{i}	Available electrical energy from SPV during the i^{th} time segment	kW
P_{WTG}^{i}	Available electrical energy from WTG during the i^{th} time segment	kW
P_{STH}^{i}	Available thermal energy from solar collector during the i^{th} time segment	kW
$P_{BT\max}$	Rating of biomass to thermal energy conversion facility	kW
$P_{ET\max}$	Rating of electrical-thermal conversion facility	kW
P_{WMG}^{i}	Available mechanical energy from WMG during the i^{th} time segment	kW
$P_{BM\max}$	Rating of biomass to mechanical energy conversion facility	kW
$P_{EM\max}$	Rating of electrical-mechanical conversion facility	kW
$P_{ME\max}$	Rating of mechanical-electrical conversion facility	kW
$P_{TM\max}$	Rating of thermal – mechanical energy conversion facility	kW

$v_{\max}^{i}$, $v_{\min}^{i}$	Maximum and minimum volumes of digester during time segment i	m^3
$N_{ST,m}$	Number of m^{th} solar thermal energy conversion facility	--
$CC_{ST,m}$	Cost of installation of m^{th} solar thermal energy conversion facility	INR
$N_{BT,m}$	Number of m^{th} biomass-thermal energy conversion facility	--
$CC_{BT,m}$	Cost of installation of m^{th} biomass-thermal energy conversion facility	INR
ST_{AV}	Number of options for solar-thermal energy conversion	--
BT_{AV}	Number of options for biomass-thermal energy conversion	--
ET_{AV}	Number of options for electrical – thermal energy conversion	--
$N_{ET,m}$	Number of m^{th} electrical – thermal conversion facility	--
$CC_{ET,m}$	Cost of installation of m^{th} electrical – thermal conversion facility	INR
SE_{AV}	Number of options for solar – electrical energy conversion	--
$N_{SE,n}$	Number of n^{th} solar-electrical energy conversion facility	--
$CC_{SE,n}$	Cost of installation of n^{th} solar-electrical energy conversion facility	INR
WE_{AV}	Number of options for wind – electrical energy conversion	--
$N_{WE,n}$	Number of n^{th} wind-electrical energy conversion facility	--
$CC_{WE,n}$	Cost of installation of n^{th} wind-electrical energy conversion facility	INR
ME_{AV}	Number of options for mechanical -electrical energy conversion	--
$N_{ME,n}$	Number of n^{th} mechanical –electrical conversion facility	--
$CC_{ME,n}$	Cost of installation of n^{th} mechanical –electrical conversion facility	INR
WM_{AV}	Number of options for wind-mechanical energy conversion	--

$N_{WM,r}$	Number of r^{th} wind-mechanical energy conversion facility	--
$CC_{WM,r}$	Cost of installation of r^{th} wind-mechanical energy conversion facility	INR
BM_{AV}	Number of options for biomass-mechanical energy conversion	--
$N_{BM,r}$	Number of r^{th} biomass-mechanical energy conversion facility	--
$CC_{BM,r}$	Cost of installation of r^{th} biomass-mechanical energy conversion facility	INR
TM_{AV}	Number of options for thermal-mechanical energy conversion	--
$N_{TM,r}$	Number of r^{th} thermal-mechanical conversion facility	--
$CC_{TM,r}$	Cost of installation of r^{th} thermal-mechanical conversion facility	INR
EM_{AV}	Number of options for electrical -mechanical energy conversion	--
$N_{EM,r}$	Number of r^{th} electrical -mechanical conversion facility	--
$CC_{EM,r}$	Cost of installation of r^{th} electrical -mechanical conversion facility	INR
N_s	Number of days in a season	--
$P_{ET,m}(s,t)$	Total power generated from the m^{th} electrical conversion facility to thermal energy during hour t of season s	kW
$OC_{ET,m}$	Operating cost of m^{th} electrical conversion facility to thermal energy	INR
$P_{ME,n}(s,t)$	Total power from n^{th} mechanical to electrical energy conversion facility during hour t of season *s*	kW
$OC_{ME,n}$	Cost of operation of converting mechanical energy into electrical energy	INR
$P_{TM,r}(s,t)$	Total power from r^{th} thermal to mechanical conversion facility during hour t of season *s*	kW
$P_{ST,m}(s,t)$	Thermal power generated from the m^{th} solar-thermal energy	kW

	conversion facility during hour t of season *s*	
$P_{ET,m}(s,t)$	Thermal power generated from the m^{th} electrical-thermal energy conversion facility during hour t of season *s*	kW
$P_{BT,m}(s,t)$	Thermal power generated from the m^{th} biomass-thermal energy conversion facility during hour t of season *s*	kW
$P_{SE,n}(s,t)$	Electrical power generated from the n^{th} solar – electrical energy conversion facility during hour t of season *s*	kW
$P_{WE,n}(s,t)$	Electrical power generated from the n^{th} wind – electrical energy conversion facility during hour t of season *s*	kW
$P_{ME,n}(s,t)$	Electrical power generated from the n^{th} mechanical – electrical energy conversion facility during hour t of season *s*	kW
$P_{WM,r}(s,t)$	Mechanical power generated from the r^{th} wind - mechanical energy conversion facility during hour t of season *s*	kW
$P_{BM,r}(s,t)$	Mechanical power generated from the r^{th} biomass - mechanical energy conversion facility during hour t of season *s*	kW
$P_{EM,r}(s,t)$	Mechanical power generated from the r^{th} electrical-mechanical energy conversion facility during hour t of season *s*	kW
$P_{TM,r}(s,t)$	Mechanical power generated from the r^{th} thermal - mechanical energy conversion facility during hour t of season *s*	kW
$N_{ST,m}^{\max}$	Maximum number of m^{th} solar thermal energy conversion facility	--
$N_{ET,m}^{\max}$	Maximum number of m^{th} electrical thermal energy conversion facility	--
$N_{BT,m}^{\max}$	Maximum number of m^{th} solar biomass energy conversion facility	--
$N_{SE,n}^{\max}$	Maximum number of n^{th} solar electrical energy conversion facility	--
$N_{WE,n}^{\max}$	Maximum number of n^{th} wind electrical energy conversion facility	--
$N_{ME,n}^{\max}$	Maximum number of n^{th} mechanical electrical energy conversion facility	--

$N_{WM,r}^{\max}$	Maximum number of r^{th} wind -mechanical energy -- conversion facility
$N_{BM,r}^{\max}$	Maximum number of r^{th} biomass -mechanical energy -- conversion facility
$N_{EM,r}^{\max}$	Maximum number of r^{th} electrical -mechanical energy -- conversion facility
$N_{TM,r}^{\max}$	Maximum number of r^{th} thermal-mechanical energy -- conversion facility

CHAPTER-1

INTRODUCTION AND LITERATURE REVIEW

1.1 GENERAL

Energy has been an important element to meet the day-to-day need of society. The development of civilization is measured by the energy utilization for human advancements or needs. The human societies are repetitively increasing the amount and form of energy flowing through each individual’s life in search of more and more comfort. Energy consumption is an absolute necessary element of industrial society. Before the industrial revolution, there were the two most relied energy sources – human and animal muscles and the energy of the wind and water available in nature. The chemical energy in firewood was the main source of heat and light. With the growth of earth’s population, the naturally occurring resources became inadequate in supplying the rising energy demands. Man found his way out through these rising demands in the form of fossil fuels that were concentrated in different parts of the world.

The rate of consumption of fossil fuels increases with time and exceed its rate of production as it takes years to produce these fossil fuels. According to present estimates, the peaking time of coal which contributes to the major share of fossil fuel, fall somewhere about the year 2040. On the other side, it takes sufficient time for a new technology to come to fruition and it is, therefore, prudent to plan for shifting the major share of energy production from fossil fuels to some other plentiful resources as early as possible. There are various plentiful resources available like solar, wind, biomass, etc.

Solar energy is one of the cleanest forms of energy. The earth's atmosphere is continuously receiving 1.7×10^{17}W of radiations from the sun. A simple calculation show that even if only one percent of solar radiation can be converted into useful energy with an efficiency of 10%, solar energy can fulfill the energy needs of the entire 10 billion population of the world.

The thermal low temperature utilization of solar energy is very economically attractive. Another example of this solar thermal utilization is solar furnaces where operating temperature as high as 4000K has been achieved. Besides, generation of steam for conventional steam turbines for the generation of electricity has also proved to be technologically feasible. The other technological solar energy extraction system is photovoltaic system. Photovoltaic solar cells utilize the energetic photons of the incident solar radiations to produce electricity directly. This technology of photovoltaic conversion is well developed but is hampered by the high cost of photocells.

Wind energy is the other plentiful resource of energy. Wind energy technology is well developed and its cost estimates are also comparable with that of other forms of energy. The large variability in the power production due to the intermittent nature of the wind hampered the large scale applications of wind energy technology even in the favorable regions.

Energy generated from biological conversion is expected to fulfill the major energy needs in the near future. Energy plantation has emerged out as the potential for sufficing the growing energy needs. In this process, appropriate plants are cultivated exclusively for the purpose of generating power either by direct bioconversion or by pyroletic conversion into liquid or gaseous fuels. Cultivation of plants like sugarcane can improve the conversion efficiency from the present 1% to 2.5%. The re-cycling processes are within the realm of possibility to convert the waste products of food and animals to methane and methanol. Hydropower, available free of cost in the form of flow water, is another important pollution free, renewable source of energy. The utilization of energy in flowing water in rivers and irrigation canals through micro-hydro schemes is a good example of appropriate technology for rural development.

Other energy sources include energy from oceans. This includes ocean thermal energy conversion, tidal energy and wave energy. High construction costs and non-uniform availability of power have hindered the progress of harnessing the tidal energy.

The above discussion led to certain merits of renewable energy sources. These are summarized as:-

- There is no danger of depletion of these sources as these can recur in nature and are inexhaustible.
- These sources are free in terms of the utilization. Renewable based power plants do not have any fuel cost and hence negligible running cost.
- There is no need for transmission and distribution of power as these sources are available in scattered manner on different sites. This results in the reduction of economic as well as technical transmission and distribution.
- There is no pollution and ecological balance problem with these sources.
- The rural areas and remote villages can be better served with locally available renewable sources of energy. There may be huge savings in transporting fuels or transmitting electricity from long distances. This can also serve the development of far flung areas and discourage the migration of population which is creating many social problems.

However, there are some demerits associated with the renewable energy sources. These are summarized as:-

- Low energy density of these sources of energy needs large sizes of the plant resulting in the plant resulting in the increased cost of the delivered energy.
- Intermittency and lack of dependability are the main disadvantages of these sources of energy.
- In some cases, construction materials used for renewable energy devices are themselves very energy intensive. For example, the photovoltaic converters require the extreme energy intensive processing of sand to crystalline silicon.

In other words, energy is one of the vital components for the economic development of a nation. Access to energy is essential for the provision of basic amenities like clean water, lighting, heating, cooking, mechanical power, etc. In developing countries, the continuously increasing energy demands pose a stringent challenge as it incurs huge investment. Energy development framework includes the access to clean, convenient and affordable energy as shown in Fig 1.1.

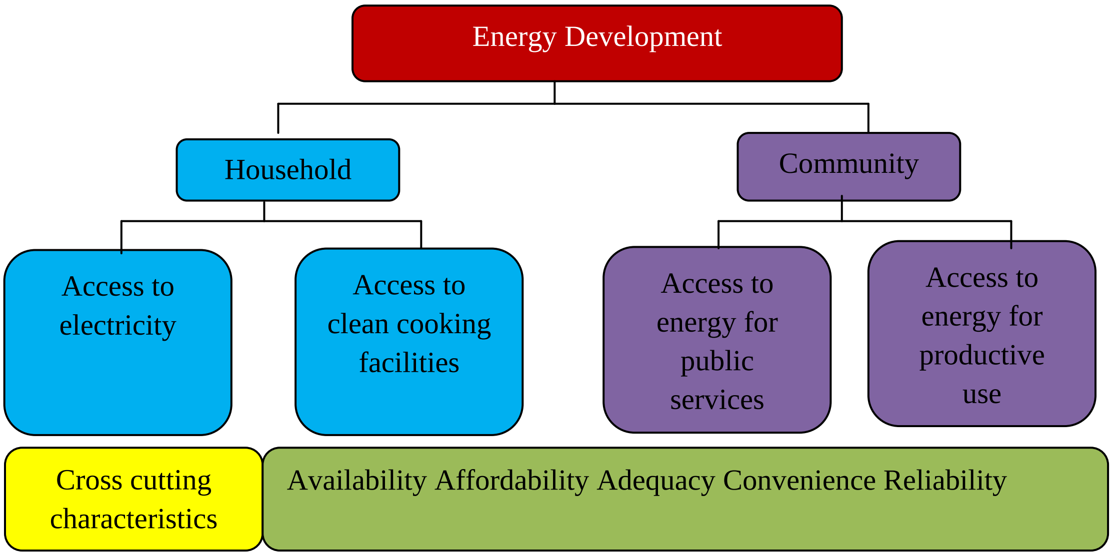

Fig. 1.1: Energy Development Framework (IEA, 2012)

As shown in Fig. 1.1, the energy development framework not only tracks energy development across different countries but also separate developments at the household and community level. In case of households, it focuses on two key dimensions: access to electricity and clean cooking facilities. When looking at community level access, it considers modern energy use for public services (e.g. schools, hospitals and clinics, water and sanitation, street lighting) and energy for productive use, which deals with modern energy use as part of economic activity (e.g. agriculture and manufacturing). The choice of indicators used is constrained by the type of data related to energy access that is currently available. This clearly emphasizes the importance of clean and convenient energy availability. Access to clean and convenient energy not only helps in the economic development but also helps in securing a healthy environment.

1.2 ENERGY SCENARIO

In developing countries, total energy consumption, per capita energy consumption and share of commercial energy sources as compared to traditional energy sources are far less than that of developed countries. Similarly, energy use in different sectors differ from country to country. Looking into the consumption pattern, there are three major energy consuming sectors – Industry, Transport and Residential. The country-wise total energy consumption is given in Table 1.1. The sector-wise trifurcation for the global energy consumption is also given in the Table 1.1. Total energy consumption of the entire world is around 8286Mtoe. The transport sector’s share is 27.7% followed by the industrial sector (27.5%) and the combined residential, services and agricultural use is 23.4%.

Table 1.1: Pattern of Energy consumption in different countries (BEE, 2014)

Country	**Total Energy Consumption**	**% of Total Energy Consumption**		
	Mtoe	**Industry**	**Transport**	**Residential**
Bangladesh	19.9	15	8.2	58.1
China	1248.2	45.9	11.1	25.3
Europe	1394.8	26	26.3	23.5
India	392.9	29	10.4	41.4
Indonesia	145.1	32.6	16.8	39
Iran	144.7	23.7	24.4	32.7
Japan	341.7	29	24.1	14.4
Malaysia	43.4	44.3	31.2	9.3
Nepal	9.5	4.6	3.1	89.6
North America	1792.8	19.5	38.7	16.7
Pakistan	68.9	27.5	16.1	47.3
Philippines	22.9	23.6	37.9	27.7
Republic of Korea	146.8	28.1	20.6	12.6
Russian Federation	429.8	29.7	21.5	26.1
Singapore	13.2	9.8	18.5	5.1
Sri Lanka	8.3	25.4	25.7	41.5
Thailand	69.6	33.3	26.1	15.2
Vietnam	48.5	21.3	16.2	56.6
World	**8286.1**	**27.5**	**27.7**	**23.4**

To get an insight of the energy scenario, a parameter called Energy Development Index (EDI) has been devised as a measure to understand the role of energy in human development. EDI provides a rigorous analytical basis for policy-making to measure energy poverty (IEA, 2012).

By the end of 21st century, as per UN projections, the world population will be about 10-12 billion. It is important to provide adequate supplies of clean, safe and sustainable energy. The extent of energy consumption draws the attention towards energy production. There are basically two categories of energy sources – conventional and non-conventional energy sources. The conventional sources include coal, gas and petroleum products while the non-conventinal energy sources include solar, wind, etc. The conventional energy resources are considered as non- renewable energy sources because of their long reproduction time. Being non-renewable, the worldwide natural reserves of coal are limited. The potential of renewable energy resources as found in literature is given in Table 1.2.

Table 1.2: Estimated renewable energy sources in EJ (EJ = 10^{18}J) (Moriarty and Honnery, 2012)

Study and Year of Estimate	Solar	Wind	Ocean	Hydro	Biomass	Geothermal	
						Electricity	Heat
Hafele (1981) (‘realizable’ potential)	NA	95 (32)	33 (16)	95(47)	189 (161)	3.2 (3.2)	47 (16)
Lightfoot/Green (2002) (range of values)	163 (118-206)	72 (48-72)	0 (1.8-3.6)	19 (16-19)	539 (373-772)	1.5 (1.5)	NA (NA)
Gross et al. (2003)	43-144	72-144	7-14	NA	29-90	NA	14-144
Sims et al. (2007)	1650	600	7	62	250	NA	5000
Field et al. (2008)	NA	NA	NA	NA	27	NA	NA
Resch et al. (2008)	1600	600	NA	50	250	NA	5000
Klimenko et al (2009) (‘economic’ potential)	2592 (19)	191(8.6)	22 (2.2)	54 (29)	NA (NA)	22 (3.6)	NA (NA)
Cho (2010)	>1577	631	NA	50	284	NA	120
Tomabechi (2010)	1600	700	11	59	200	NA	310,000
WEC (2010)	NA	NA	7.6	57.4	50-1500	1.1-4.4	140
All studies range	118-2592	48-600	1.8-33	50-95	27-1500	1.1-22	14-310,000
Earth Energy Flows	3,900,000	28,400	700	130-160	3000	1300	

1.2.1 Indian Energy Scenario

India’s absolute primary energy consumption is only 3.8% of the world, 20% of USA and 85% of Japan. A substantial amount of improvement, therefore, is needed to elevate the standard of living of Indian people to a greater height and thereby put India into its rightful place in the list of advanced nations as far as the per capita energy consumption is concerned. India is one of the largest producers of coal and lignite in the world. Most of these are high ash content coal (30-45%) and the calorific value in the range of 3000-4500 kCal/kg. The coal produced in the country is not sufficient to meet the current demand of the country. To meet this demand, higher calorific value and low ash content coal is being imported from Australia, Indonesia and South Africa (BEE, 2014).

Indian oil reserves are estimated around 5.8 billion barrels. Oil accounts for about 31% of the country’s primary energy consumption at the end of 2008. Sector-wise, transport accounts for 42% followed by domestic sector and industry sector with 24% each (BEE, 2014). Indian gas reserves are estimated to 1,437 billion cubic meters in 2010 which amounts to about 0.6% of the total world reserves. The sector-wise energy consumption in India is given in Table 1.3.The table shows 14% energy consumption in residential sector. There is a very wide difference in the energy consumption pattern of the rural and urban households. Despite having a major population of rural households, the demands for oil, gas and electricity accounts for only 42%.

Table 1.3: Indian sector-wise energy consumption (BEE, 2014).

Sector	Energy Consumption	
	Mtoe	%
Industry	102.94	45
Transport	40.31	18
Residential	31.44	14
Agriculture	16.76	7
Commercial	3.51	2
Other energy uses	16.54	7
Non-energy uses	18.36	7

1.2.2 Energy Demands in Rural Areas

The wide difference between energy consumption patterns in rural and urban area is credited to the unavailability of commercial energy resources (Barnes and Floor, 1996). The rural energy needs are mainly suffice by the non-commercial energy resources like wood, animal dung and crop residues. Energy scenarios in rural areas may broadly be classified into the under given categories (Devadas, 2001).

i) Household energy consumption
ii) Energy consumption in agriculture
iii) Energy interactions in rural systems
iv) Assessing economic feasibility of technologies in the rural systems
v) Impact of technology in the rural systems
vi) Rural energy planning at the micro level

Considering different energy scenarios, the rural energy demands may be categorized as:

- Household energy demands

  The household energy demands include energy for cooking, heating and lighting. The factors influencing the household energy demands include availability of resources, occupation, income level and size of land farms (Devadas, 2001).

- Agricultural energy demands

  The agricultural energy demands depend upon the agro-climatic conditions, availability of irrigation resources and the choice of crop. The irrigation exercise in agriculture is the main energy consumer in the agricultural energy demands (Devadas, 2001).

India is essentially an agricultural country with 78% of its population living in rural countryside and 70% of its GDP emanating from rural agricultural sector. There are more than half a million villages across the length and breadth of the country. About 95% of these villages are small and scarcely populated with very low demand factor. It is, therefore, not economical to electrify them from power grids. The development, welfare and prosperity of rural villages depend upon the availability of following services:

- Cooking energy is 80% of the basic rural energy needs.
- Water for drinking, irrigation and washing.
- Domestic amenities: Lighting and heating.
- Community services: Radio and TV sets, street lighting and cooperative milk chilling.
- Utilities for village industries: Power, water and steam.

- Food supply system.

1.2.2.1 Cooking in rural areas

Cooking sector is considered as one of the major energy consuming sector in developing countries. As cooking is an important daily household activity, it consumes significant amount of energy and human effort. It is easier for people living in urban areas as the availability of resources made cooking a clean and effortless exercise. But in rural areas, particularly in developing countries, cooking is a mammoth of a task. Even with the advent of technologies in this area, people are still dependent on traditional methods of cooking. These traditional methods are not only inefficient but also cause indoor pollution. In India, a large number of rural households are still dependent on bio-fuels for cooking purpose. According to 2011 census, about 70% of rural Indian population rely primarily on unprocessed solid fuels— firewood, cow dung and crop residue (www.censusindia.gov.in). Agrawal and Singh (2001) studied the conditions in the rural households of Uttar Pradesh (India) and suggested various energy options for such house-holds.

Indoor air pollution remains a noteworthy global health menace that needs to be addressed. The literature indicates that ambient air pollution levels and personal exposure levels from cooking with traditional fuels are severely high. Cooking with traditional solid fuels on open flames or traditional cooking stoves may result in exposure to extremely damaging toxic pollutants. Moreover, incomplete combustion leads to the release of small particles and other constituents that have shown to be damaging to human health in the household environment. Further, it is estimated that there are nearly 2.44 million deaths attributable to biomass indoor particle air pollution in developing countries. These may be due to the improper ventilation and incomplete combustion of biomass and other fuels used to meet residential cooking needs. The share of clean fuels is still a far away thing. Purohit et al. (Purohit et al., 2002) estimated the potential of renewable energy technologies for cooking in India. Although solar and biogas energy technologies are quite mature technologies, their applications in India are still very limited. Quadir et al. (1995) discussed various barriers to dissemination of renewable energy technologies in cooking sector.

A wide variety of resources are being used as fuels for cooking. These include fuel wood, kerosene, Liquefied Petroleum Gas (LPG), electricity, biogas, biomass and solar energy. In addition, Ramanathan and Ganesh (1994) considered coal, soft coke, lignite, natural gas, charcoal as other cooking energy sources. The income of the household is the main determinant of the selection of fuel for cooking. The other factors contribute to the fuel selection for cooking are fuel availability, seasonal income variation and power relations within household (Soussan et al., 1990). It was also concluded that the energy transition is only possible in case of the availability of the alternatives and that is why the transitions are there in urban and sub-urban areas only (Laar, 1991). Table 1.4 gives the share of households using particular fuel for cooking (Reddy, 2013).

Table 1.4: Percentage share of households using particular fuel for cooking (Reddy, 2013)

Income Class (Rs/month)	**Fuel Wood**	**LPG**	**Dung**	**Kerosene**	**Coal**	**Biogas**	**Electricity**	**Others**	**Total**
Rural Households									
Low Income	29.24	0.16	3.85	0.24	0.61	0.01	0.00	1.37	35.5
Middle Income	39.36	2.14	5.59	1.35	0.72	0.15	0.04	1.66	51.0
High Income	6.95	3.10	1.18	1.12	0.23	0.16	0.04	0.73	13.5
Total	75.54	5.40	10.62	2.71	1.56	0.32	0.08	3.77	100.0
Urban Households									
Low Income	15.24	5.04	1.26	7.13	2.08	0.01	0.08	1.92	32.8
Middle Income	6.81	28.16	0.76	13.11	2.07	0.04	0.25	1.98	53.2
High Income	0.25	11.01	0.04	1.50	0.10	0.00	0.08	1.09	14.1
Total	22.29	44.21	2.06	21.74	4.25	0.05	0.40	4.99	100.0

It is self evident that the major portion of cooking needs are supplied through fuel wood as fuel in rural areas. Secondly, the penetration of clean fuel for cooking purposes is almost negligible in rural areas. In India, traditional solid biofuel is still widely used for meeting cooking and space conditioning needs. Solid biofuel has traditionally been used in rural areas as cooking fuel, particularly by poor (Ravindranath, 2009).

1.2.2.2 Efforts and initiatives on rural cooking energy

In the rural cooking energy sector efforts have been ongoing for over three decades. Government of India (GoI) initiated several programmes and schemes for the dissemination of clean and efficient technologies for cooking and other thermal applications. Some of the programmes are listed below:

a) National Biogas and Manure Management Programme (NBMMP)

NBMMP is being implemented in the country since 1981-82 for promotion of biogas plants based on cattle dung and other organic wastes. The NBMMP mainly caters to setting up of family type biogas plants for meeting the cooking energy needs in rural areas of the country along with making enriched bio-fertilizer availability to farmers. With the installation of 4.31 million family type biogas plants by January 2011, about 35% of the estimated potential has been realized so far. It is estimated that the construction of 1,19,914 biogas plants would have generated about 3.35 million person-days of employment for skilled and unskilled workers in rural areas during the year.

b) National Programme on Improved Cookstoves (NPIC)

The National Programme on Improved Cook stoves (NPIC) was started by the Ministry of Non-conventional Energy Sources (MNES), Government of India, in 1985 to achieve the twin objectives of fuel wood conservation and smoke reduction in kitchens. NPIC has overseen the installation of 28 million improved cook stoves, saving nearly 20 million tons of firewood per year (Kilice et al., 1983).

c) National Biomass Cook stove Initiatives

The Ministry of New and Renewable Energy (MNRE), Government of India on 2nd December 2009 launched National Biomass Cook stoves Initiative (NBCI) at New Delhi with the primary aim to enhance the availability of clean and efficient energy for the energy deficient and poorer sections of the country. The initiative emphasizes on enhancement of technical capacity in the country by setting up state-of-the-art testing, certification and monitoring facilities and strengthening R&D programmes in key technical institutions (MNRE, 2014).

d) Jawaharlal Nehru National Solar Mission

The main objective of JNNSM is to promote off-grid applications of solar energy (both SPV and solar thermal). Various off-grid solar photo voltaic systems / applications up to a maximum capacity of 100 kWp per site and off-grid and decentralized solar thermal applications, to meet / supplement lighting, electricity/power, heating and cooling energy requirements would be eligible for being covered under the scheme. For rural electrification through mini-grids, applications up to a maximum capacity of 250 kW per site would be supported (MNRE, 2014). As per the annual report of MNRE, a summary of the targets and the achievements are as given in Table 1.5 (MNRE, 2014).

Table 1.5: Physical Target and Achievement Made during 10^{th} Five Year Plan (MNRE, 2014)

Name of the Scheme/ Project/ Program	Units	2003-04		2004-05		2005-06		2006-07		Xth Plan	
		T^a	A^b	T	A	T	A	T	A	T	A
Biogas Plants	No. in Millions	0.149	0.141	0.1	0.109	0.066	0.061	0.1	0.096	0.568	0.560
Solar Cooker	×1000 Nos	35	5	35	20	35	19.769	22	16.209	162	70.978
SWHS	$\times 1000 m^2$ collector area	55	0	100	150	400	400	400	400	1005	995

[a]Target; [b]Achievement

1.2.2.3 Electrification in rural areas

Providing electricity in rural areas, particularly in developing economies, is challenging for three primary reasons. First, rural populations are usually dispersed and have low consumption, resulting in high capital costs spread over low returns. Second, the ability to pay of many rural populations is low, making centralized grid expansion unable to recover costs. Third, generation shortages, long rural feeder lines and poor maintenance often result in low quality power being delivered erratically to rural consumers (Foley, 1992a; 1992b).

Despite these challenges, with a few notable exceptions, universal access programs have generally been implemented through the centralized utility system. Of course, centralized utilities do have an important role to play in rural electrification. For many rural customers, the grid is the lowest cost option available and will thus be the dominant mode of electrification. However, the high costs of extending grids to rural areas, the lower ability of rural customers to pay for electricity service, and the financial instability of many utilities in these regions mean that some rural areas will not gain access to the grid in the foreseeable future. There is nothing, however, in the theoretical goal of universal electricity access that requires it to be met through centralized utilities (Chaurey et al., 2004).

Over the past few decades a number of small-scale, autonomous power generation technologies that are suitable for rural areas have been developed or improved. Autonomous power generation is attractive for rural electrification for a number of reasons. For example, the low population densities and low consumption of rural customers are well matched to the scalability and autonomous operation possibilities of distributed power. Grid extension is expensive in rural areas and generally means trying to provide electricity that is available (in theory, at least) 100% of the time and at levels that may be much higher than typical rural consumption levels. In addition, rural customers will have an even greater imbalance than urban ones between their minimum and maximum (peak) loads. Many rural customers do not have refrigerators or other appliances requiring constant power and will use their electricity in the evening hours only for lighting, entertainment and, in some cases, cooking. While rural consumption is relatively low, its additive effect right at the time of peak power demand on the system can force the utility to run more expensive generating units more often or even to invest in new peaking generation. This can significantly raise the cost of supplying rural customers (Zerriffi, 2011). Autonomous generation facility is able to provide power at levels and at times that are well-matched to rural customers.

1.3 RENEWABLE ENERGY SYSTEMS

Energization of rural areas will improve the quality of living of the people and thereby, the development of the nation. Providing energy to rural areas has a strong association with rural electrification.

However, extending the grid to supply remote loads is not always cost effective. The term energization involves the use of several energy forms of different quality and characteristics to provide a variety of energy and other needs like cooking, water supply, lighting, educational and communication devices, small scale industry, etc. The key is to match the needs with the resources to maximize the end use efficiency and minimize cost (Ramakumar, 1996).

1.3.1 Integrated Renewable Energy Systems

Many studies have shown that the solar and wind energy potential would be far more than the entire energy demand of the globe. The increasing deployment of renewable energy resources raises challenges and opportunities regarding their integration utilization. The planning and development of integrated energy must consider the availability of energy sources, system and local demands where it is desirable to install a renewable energy source. Resource-demand matching in an optimized manner is the main consideration in an Integrated Renewable Energy Systems. An integrated renewable energy system has been presented in Fig.1.2, to determine the optimum allocation of different renewable energy sources for various end-uses in India for the year 2020-21 (Iniyan et al., 1998; Jebaraj and Iniyan, 2006).

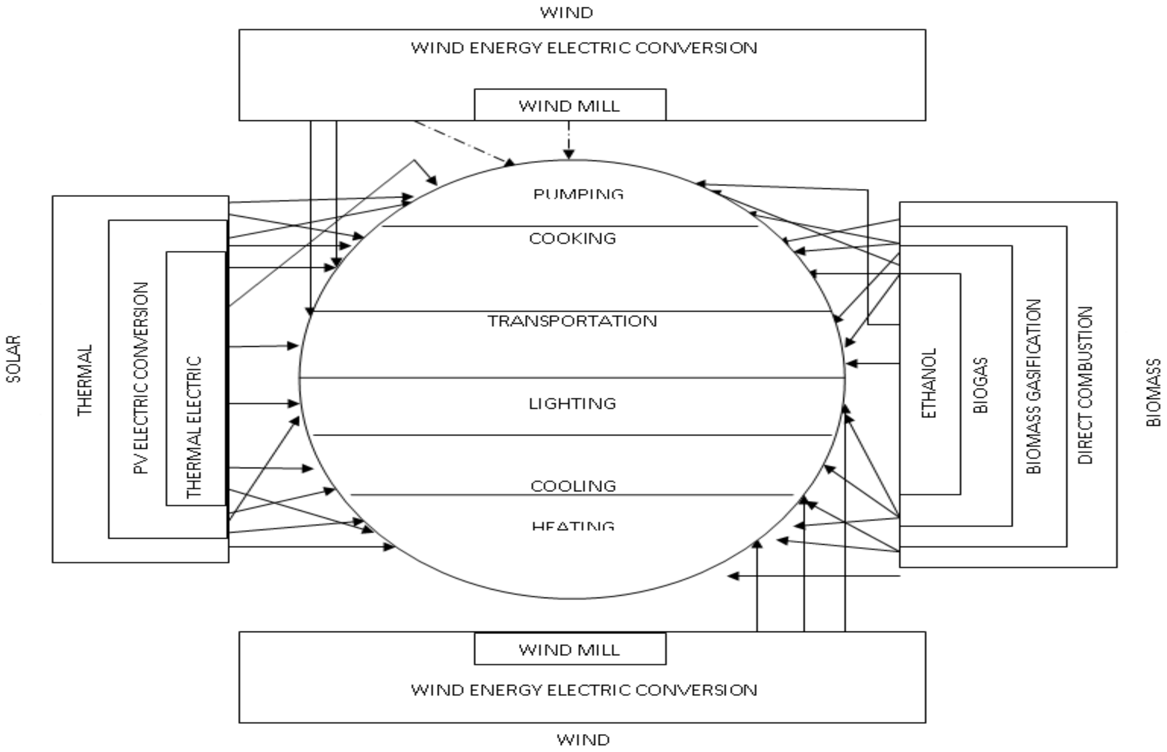

Fig. 1.2: Optimum renewable energy model (Iniyan and Jagadeesan, 1998)

Supplying energy to a variety of loads by harnessing two or more renewable energy sources in tandem can be accomplished in two basic ways - convert all the resources into one form (typically electrical because of its versatility) for supply and storage. The term hybrid is often used in this context. Secondly, matching the resources, needs and technologies to maximize end-use efficiency and minimize cost. The first approach, though convenient, is not always economical and does not result in the most efficient use of resources. The second approach invariably results in an economically viable option (Ramakumar, 1989). Systems utilizing two or more renewable energy sources and two or more end use technologies to supply a variety of energy and other needs are called an Integrated Renewable Energy System (IRES) (Abouzahr and Ramakumar, 1993). Typically such systems are operated in a standalone mode with energy storage in several different forms. Energizing using IRES starts with a-priori matching of the available resources, needs and energy conversion, storage and utilization technologies as much as possible to maximize end-use efficiency and minimize cost. Some of the matches of needs and resources that appear appropriate at present are as given in Table 1.6.

Table 1.6: List of need-resource matches (Abouzahr and Ramakumar, 1993)

S.No.	Types of Needs	Resources
1.	Cooking	Biogas stoves, woody biomass with improved cookers
2.	Water Supply (Domestic and Potable)	Wind driven mechanical water pumps, PV driven water pumps, Biogas fueled engine/pump sets
3.	Lighting (Domestic and Street)	Electricity from village level IRES with multiple sources – PV, Wind electric conversion system, Biogas fueled engine/generator system
4.	Cold Storage	Electricity from village level IRES
5.	Educational and Communication Services	Electricity from village level IRES with battery storage
6.	Irrigation water	Wind driven mechanical water pumps, PV driven water pumps, biogas fueled engine/pump sets

Contd…..

7.	Low-grade thermal energy	Flat plate solar collectors
8.	Small scale industries	Electricity from village level IRES; Concentrating solar collectors for process heating
9.	Energy Storage	Biomass and biogas storage, Potential energy of water stored small amounts in secondary batteries

Designing of IRES include the ratings of the various energy conversion and energy storage devices required to supply all the energy and other needs of the locale or village. Different renewable energy resources like solar, wind, hydro, and biomass are considered for matching the needs. In addition to these resources, battery and diesel generator is also used for the storage of extra energy generated during lean period or meet out the shortage during the peak period. The most logical approach to arrive at these figures is the one that strives to supply energy to the different loads at a preselected reliability level and at minimum annual cost (Abouzahr and Ramakumar, 1993).

1.3.2 Different Combinations of Energy Resources

Several configurations of renewable energy resources are possible depending upon the type of load. Depending upon the availability of resources, researchers have developed various models to assess the performance and thereby, to meet out the demand optimally and reliably. As electrical energy is the most convenient form of energy so the priority of the researchers has been the generation of electrical energy from these resources. Vera (1994) presented a system comprising of photovoltaic, wind, diesel generator and micro-hydro and develop a real time controller for the dispatch of power. Sreeraj et al. (2010) presented a methodology for the design of isolated hybrid renewable energy system.

Borowy and Salameh (1996) considered a photovoltaic, wind and battery based system and obtained an optimal size of battery and photovoltaic system. They calculated the optimum number of batteries and PV modules for a desired loss of power supply probability. Karaki et al. (1999) considered a similar system with PV, wind and battery storage system and develop a probabilistic model considering outages due to power fluctuations and hardware failure. The maximum size of battery has been obtained with the parameter of expected energy not supplied.

Nehrir et al. (2000) simulated a PV, wind and battery based hybrid system and the performance of the system has been evaluated such that the sizes of the system can be obtained before the installation of the system. Prasad and Natarajan (2006) considered a solar-wind integrated system for rural electrification. Based on certain parameters like deficiency of power supply probability, relative excess power generated, unutilized energy probability, life cycle cost, levelized energy cost and life cycle unit cost, the optimization has been performed to obtain the sizes of the system.

Ai et al. (2003) considered a PV/wind based hybrid system. The mathematical models have been developed in order to obtain the optimum sizes. Later, a trade-off has been done between the different capacities of PV array and battery bank for a desired loss of load probability. Diaf et al. (2008) presented the design of PV-wind-battery based system and performed the techno-economic analysis for particular energy autonomy with minimum levelised cost of energy. It has also been concluded that the hybrid systems are better than stand-alone PV and wind energy systems in terms of economy.

Yang et al. (2008) simulated a hybrid system with PV-wind and battery sources and analyzed the reliability of the system considering the loss of power supply probability as the parameter. Yang et al. (2007) considered a PV-wind system with battery bank and determined the optimal sizes of the sources such that the system is reliable even under variable weather conditions. The loss of power supply probability as the reliability parameter and the annualized cost of system as the economic parameter have been considered in the study.

Habib et al. (1999) studied a stand-alone solar – wind energy conversion system and presented an optimization procedure to satisfy a given load distribution. Optimum size of the system has been obtained by varying the solar/wind power ratio with minimizing the capital cost. Kolhe et al. (2003) presented a solar-wind based hybrid system with hydrogen production for long term energy storage. The contribution of PV array power output has been determined using solar radiation usability concept. The operation of fuel cell generator and electrolyser has been varied as per the electrical energy output from renewable energy systems.

Fadia et al. (1997) designed a PV wind based autonomous system with battery bank as storage system and considered loss of power supply probability as the design parameter. Chedid et al (1998) studied a grid connected solar wind system. The design considered the influencing factors that relate to the political and social conditions in addition to technical advances and economics. Abouzahr and Ramakumar (1993) presented a utility interactive wind based energy conversion system and studied the performance of the system using convolution based probabilistic approach. Borowy and Salameh (1994) considered a PV wind based hybrid system and calculated the optimum size of PV array using the least square method to determine the best fit of PV array and wind turbine to a given load.

Notton et al. (1996) considered a system with PV, diesel generator and battery as the sources. The optimum sizes have been obtained using the energy balance concept optimizing the contribution from each source. El-Hefnawi (1998) studied a PV, diesel generator and battery system with the objective of minimizing the cost of PV system via minimization of PV array area and storage system. The number of days of autonomy has been taken as the parameter for the battery storage system. Dufo-Lopez and Bernal-Agustin (2009) considered a PV-diesel hybrid system in their study. They advocated the optimal design of these systems in order to get more cost effective and reliable system than PV systems alone.

Vieira and Ramos (2009) presented a combination of wind hydro system. Optimization has been done to obtain the operational strategy of the pump. An energy cost comparison is made with normal operating mode and the optimized operating mode. Kaldellis et al. (2001) explored the possibility of creating a wind-hydro based energy station for a remote island load site. A techno-economic analysis has been performed to find out the appropriate number of wind turbines and optimum sizes of water reservoir.
Dursun et al. (2011) proposed an integrated wind-hydro system to improve the reliability of the system by considering the stochastic behavior of wind speed. They proposed a

methodology to obtain the optimum sizes of the system and then the most beneficial system has been obtained after applying this method to six different sites. Dursun and Alboyaci (2010) examined the importance of wind- hydropower combination in context of Turkey and elaborated the advantages of hybrid energy systems. They have also emphasized the contributions of wind-hydropower combination in meeting Turkey's electric energy demand.

Jaramillo et al. (2004) focused on improving the reliability of the system by overcoming the intermittency of wind energy through complementing wind power with hydro power. The techno-economic analysis has been performed to obtain the levelized production cost of the hybrid system. Ashok (2007) proposed a combination two or more renewable energy resources like solar photovoltaic, wind turbines, micro-hydro and conventional generators for rural electrification. For the selected site, the wind-microhydro system was found to be optimal in terms of life cycle cost.

Dhanapala and Wijayatunga (2002) considered two indigenous sources of biomass and micro-hydro for energy supplies to a tea plantation unit. The effect of substitution of these resources for meeting out the demand in tea plantation sector as well as in the national energy scenario has also been examined.

Margeta and Glasnovic (2010; 2011) considered a PV, hydro-electric system to achieve optimal renewable energy production in order to increase the share of renewable energy sources in electric power system. Nfah andNgundum (2009) incorporated a PV, pico-hydro with a biogas generator for a remote electrical load in Cameroon, Africa. The hybrid system has been simulated to make the feasibility study. It was found that the biogas based renewable energy systems could be considered for the supply of energy to key sectors involved in poverty alleviation. Instead of using hydro-power alone, Kenfack et al. (2009) suggested a judicious combination of different resources like solar PV along with battery and diesel generators for rural electrification. The optimum sizes of different generators have been obtained for a rural load site at Cameroon, Africa.

Muhida et al. (2001) studied a PV and micro-hydro system installed in Indonesia. The merits of both the resources have been exploited to obtain the optimum result. Micro-hydro complemented the photovoltaic during weather uncertainty. Ehnberg and Bollen (2005) compared different cases that include solar power only; solar power with storage; solar and hydro-power and solar and hydro-power with storage. It was found that a combination of resources is required to secure the reliability of the system.

Perezz-Navarro (2010) utilized biomass based energy generation in combination with wind generators to compensate for the intermittency in the wind power. The hybrid system design parameters have been obtained such that the wind prediction errors have been mitigated. Denholm (2006) proposed a complete renewable based electricity generation system considering wind energy, compressed air storage and biomass gasification. The system was developed by replacing the natural gas with biomass gasification in order to mitigate the carbon dioxide emissions.

Jurado and Saenz (2002) explored the possibilities of integrating wind energy system with biomass based power plant and diesel generator. It was found that the developed model was valid for robust control strategies. Jurado and Saenz (2002) considered a wind-biogas-diesel based system to supply the power needs of a rural site. The adaptive control scheme has been developed to optimally dispatch power from different resources and compensating for the uncertainty in the wind power. Jurado and Saenz (2002) considered wind with diesel generator and developed a neuro-fuzzy based controller in order to achieve optimal time domain performance of the system under wide range of varying operating conditions.

Waldau and Ossenbrink (2004) presented an overview of the growth of renewable energies in Europe particularly solar photovoltaic, wind and biomass. Mason et al. (2010) explored the possibility of 100% renewable based energy generation system replacing fossil fuel based generation with wind generators in Newzealand. The hydro-power generation covers almost 60% of installed capacity. Other resources considered in the study were biomass and geothermal. Ramakumar (1983; 194; 195; 196) raised concerns about the increasing energy demands and economic and geopolitical constraints on global non-renewable energy supplies. He advocated the use of integrated renewable energy systems based on resource-demand matching. A combination of resources like solar, wind, biomass and micro-hydro has been presented to supply various electrical, mechanical and thermal needs.

Kanase Patil et al. (2010) integrated different energy sources like PV, wind, biomass, biogas and micro-hydro to supply various energy needs of a remote rural site. They obtained the sizes of different resources while minimizing the cost of energy and considering different scenarios. Dufo-Lopez and Bernal-Agustin (2005) presented a PV-wind-diesel system and worked out the optimum configuration of the system as well as the control strategy by simultaneously minimizing the total cost through the useful life of the installation and the pollutant emissions.

Abdullah et al. (2010) considered a system with diesel, solar, hydro generators and fuel cells for rural electrification of an ICT telecenter. The cost effectiveness has been compared with a stand-alone PV system and the combined power schemes. Besides, an improvement of efficiency has also been observed. A combination of wind, microturbine, solar array and battery storage system has been considered by Kalantar et al. (2010) to perform the economic analysis and also the dynamic behavior of the system has been simulated and a controller has been designed to manage the captured energy by the resources and the consumed energy by the loads.

Gupta et al. (2010) developed a mathematical model for a combination of resources like solar, micro-hydro, biomass, biogas, and diesel generator along with the balance of system components. Sinha (1993) considered a combination of wind, hydro and diesel power plant with pumped storage. Sinha developed a model to evaluate the performance and economics of the system. The system has then been applied to a hypothetical site. Dufo-Lopez and Bernal Agustin (2008) designed a PV-wind-diesel-hydrogen-battery system. The best combination of resources and their control strategy has been obtained considering the objectives of cost, emissions and unmet load. Ashok and Babu (2009) worked out a utilization strategy for different renewable energy resources in context of industrial load management.

Balamurugam et al. (2009) presented a combination of biomass-wind-PV based system for supplying rural needs. Dihrab and Sopian (2010) discussed the feasibility of a hybrid PV-wind system for electricity generation in Iraq. Kaldellis (2007; 2010) proposed renewable based hybrid system, mainly comprising of PV/wind/diesel for remote loads like telecom station and for rural electrification needs.

Bhattti et al. (1997) discussed the technical aspects of wind-diesel based hybrid power system. Chedid and Rahman (1997) considered a wind – solar based hybrid system and worked out a sizing methodology for the hybrid system. Kellog et al. (1996; 1998) also developed a sizing methodology for a hybrid system comprising of wind and PV energy resources.

Kumaravel and Ashok (2012) discussed a hybrid system comprising of biomass-PV-picohydro energy resources and developed an optimal system for electrification of a remote and isolated village in Western Ghats of India. Roy et al. (2009; 2010) considered an hybrid system with wind and battery as the energy resources and worked out an optimum sizing strategy for the system. Sharma and Bhatti (2013) performed a performance investigation of a wind-diesel based hybrid power system. A summary of different combination of resources considered by the researchers worldwide with their objectives of research is presented in Table 1.7.

Table 1.7: Different combination of resources

System	Objective	References
PV-Wind-Battery	Sizing of PV array and battery bank is done.	(Borowy and Salameh, 1996)
	Assessed expected energy not supplied with or without battery	(Karaki et al., 1999)
	Simulation of hybrid system has been done to evaluate the performance of the system.	(Nehrir et al., 2000)
	To develop an optimum system for a rural site.	(Prasad and Natrajan, 2006)
	Hay's model is used for solar panel modeling and wind turbine characteristics are obtained by fitting practical characteristic curve using least square method.	(Ai et al., 2003)
	Different components of solar radiations are modeled separately.	(Diaf et al., 2008)
	Simplified wind turbine and PV modules are used for generated power calculation	(Yang et al., 2008)
	Sizing has been done minimizing the annualized cost of the system.	(Yang et al., 2007)
PV-Wind	Optimum size of the system has been obtained by varying the solar/wind power ratio.	(Habib et al., 1999)
	Study of Integrated PV-Wind system for long term energy storage as hydrogen	(Kolhe et al., 2003)
	Hybrid system has been designed on the basis of Loss of Power Supply Probability (LPSP)	(Fadia et al., 1997)
	Simulation of the hybrid system has been done based on the pre-decided priorities	(Chedid et al., 1997)

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	Develop an optimal sizing methodology	(Kellog et al., 1996; 1998)
	Optimum size of PV array has been obtained using analytical approach	(Borowy and Salameh, 1996)
	Sizing and control methodology has been worked out	(Chedid and Rehman, 1997)
	Feasibility study has been done	(Dihran and Sopian, 2010)
	Wind system and PV system has been compared for rural electrification	((Kaldellis et al., 2007)
PV-DG-Battery	Sizing is done based on the calculation of wasted energy and energy deficit	(Notton et al., 1996)
	Sizing is done based on number of days of autonomy and depth of discharge.	(El-Hefnawi, 1998)
	Two stage algorithms are used for the determination of optimal sizes of resources.	(Agustin and Lopez, 2009)
Wind-Hydro	To develop an optimum model for energy efficiency in water supply systems	(Vieira and Ramos, 2009)
	To perform a techno-economic study for a remote island.	(Kaldellis et al., 2010)
	To optimally integrate hydropower to supplement for wind power variability.	(Dursun et al., 2011)
	To examine the importance and necessity of wind-hydro pumped storage systems in context of Turkey.	(Dursen et al., 2010)
	To establish hydropower as a complement of wind power.	(Jaramilo et al., 2004)
	To develop an optimized model for community.	(Ashok, 2007)
Wind-Battery	To develop an optimum sizing methodology	(Roy et al., 2009;

Contd…..

		2010)
Wind-Diesel	To investigate the performance of the hybrid system	(Sharma and Bhatti, 2013)
Biomass-Hydro	To perform an environ-economic study for biomass-hydro based system.	(Dhanapala and Wijayatunga, 2002)
PV-Hydroelectric	To achieve optimal renewable energy production in order to increase the share of renewable energy sources in electric power system.	(Margeta and Glasnovic, 2010; 2011)
	To make a feasibility study of PV and Pico-hydro based systems in African context.	(Nfah and Ngundam, 2009)
	To develop an optimum renewable based system for rural electrification.	(Kenfack et al., 2009)
	To present a review of the performance of 10 years operation of PV-Micro-Hydro based system.	(Muhida et al., 2001)
	To study the reliability of solar-hydro based system.	(Ehnberg et al., 2005)
Biomass-Wind	To develop a reliable source of electricity by integrating biomass gasification power plant with wind generators	(Perez-Navarro et al., 2010)
	Biomass based storage for technical, environmental and social improvement of wind energy system	(Denholm, 2006)
	To perform a feasibility study for biomass-wind integration	(Jurado and Saenz, 2002)
Biomass based Diesel-Wind	To develop and adaptive control scheme for a hybrid system.	(Jurado and Saenz, 2003)
	To develop a neuro-fuzzy controller for a	(Jurado and Saenz,

Contd…..

	wind-diesel system.	2002)
Biomass-Wind-PV	To make a review on progress for Biomass-wind-PV based system in context of European Union.	(Jager-Waldu and Ossenbrink, 2004)
	To study the feasibility of the hybrid system.	(Balamurugan et al., 2009)
Hydro-Wind-Geothermal-Biomass	To develop a 100% renewable based system.	(Mason et al., 2010)
Solar(PV/Thermal)-Wind-Biomass-Falling water	Study in viability of renewable energy resources for rural applications	(Ramakumar, 1983; 1994; 1995; 1996)
PV-Wind-BES-Biogas-MH	Integration of all the available resources has been done to meet out the rural needs.	(Kanase-Patil et al., 2010)
PV-Wind-DG-Battery	Hybrid system has been designed with the optimization objectives of minimizing cost and pollution	(Bernal-Agustin and Dufo-Lopez, 2009)
Solar-Hydro-Diesel-Fuel Cell	To review and make a comparative study for different hybrid schemes.	(Abdullah et al., 2010)
PV-Wind-Micro-turbine-Battery	To develop and simulate a dynamic model of a renewable based system.	(Kalantar and Mousavi, 2010)
Micro-hydro-Biomass-Biogas-PV-Diesel-Battery	To develop a renewable based system for rural electrification.	(Gupta et al., 2010)
Wind-Hydro-Diesel	To perform a techno-economic study for a hypothetical site.	(Sinha, 1993)
PV-Wind-Diesel-Hydrogen-Battery	To develop an optimal system on the basis of –minimum cost, emissions and unmet load.	(Dufo-Lopez and Bernal-Agustin, 2005)
PV-Biomass-Picohydro	To develop an optimal system for rural isolated village in India	(Kumaravel and Ashok, 2012)

Electrical energy, being the most convenient form of energy, was the motivation behind the development of such systems. Such systems have been designed from an economic perspective or from a techno-operational perspective. Economic optimization criteria include total energy systems costs, capacity costs and societal costs. From a techno-operational perspective, optimization criteria include fuel savings, CO_2 emissions, reserve backup capacity, elimination of excess power generation and generation at minimum reliability.

1.4 MATHEMATICAL MODELING OF RESOURCES

Different classifications of models of renewable energy systems such as renewable energy models, emission reduction models, energy planning models, and control models using optimization methods are found in literature. A resource-wise review of different models is presented as follows;

1.4.1 Solar Energy System

Solar energy is the most abundant, inexhaustible and clean of all renewable energy resources till date. The power from sun intercepted by the earth is many times larger than the present rate of all the energy consumption (Parida et al., 2011). Solar energy can be used through two routes – the thermal route uses the heat for water heating, cooking, drying, water purification, power generation and other applications. Seyboth et al. (2008) discussed the potential for solar energy in heating and cooling applications. Shammugam and Natarajan (2006) discussed solar energy for drying applications. The photovoltaic route converts the solar energy into electricity which can be used for a number of purposes such as pumping, communications and power supply in un-electrified areas.

1.4.1.1 Solar thermal system

The use of solar radiations to heat a working fluid (water or air) is the basis of solar thermal systems. Fig. 1.3 shows the classification of solar thermal systems based on the working fluid temperatures achieved and the end uses.

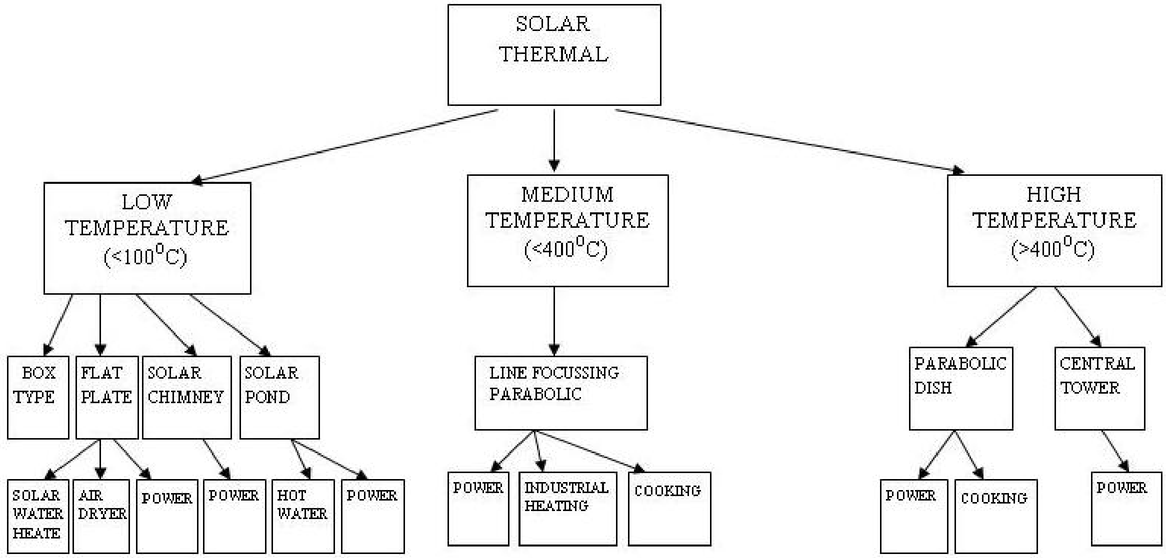

Fig. 1.3: Classification of solar thermal system

One of the main applications of the solar thermal system is solar cooking. A solar cooker is an environmental friendly and cost effective device for harnessing solar energy. Schwaizer et al. (2007) investigated various designs and characteristics of solar cookers. Garg et al. (1983) predicted a mathematical model for a single-glazed hot box type solar cooker based on partial differential equations obtained directly from applying energy balance equations. Prasanna and Umanand (2011) proposed a hybrid cooking technique which satisfied the limitations associated with solar cooking. They considered the following limitations;

- The cooking should be done without moving out of the kitchen.
- A reduction in the use of the thermal energy.
- Cooking can be carried out only in day-time.
- Time taken for cooking must be comparable with conventional cooking.

A bond graph model has been proposed which combines different domains like thermal, electrical and hydraulic. Another way of utilizing solar thermal energy is through solar ponds. A solar pond is a shallow body of water in which a stabilizing salinity gradient prevents thermal convection thereby allowing the pond to act as a trap for solar radiation. A major advantage of solar ponds over other collectors is the ability to store thermal energy for long periods of time. This advantage attracted researcher all around the globe to study solar pond. Bryant and Colbeck (1977) proposed a solar pond for London. Assaf (1976) and Tabor (1963) proposed alternative designs for solar ponds. Rubin and Benedict (1986) developed a mathematical model to provide a complete analysis of pond heating up processes and heat extraction processes.

Electrical energy can also be generated through solar thermal route of utilization of solar energy. This is through solar thermal power plants. Sangi et al. (2011) presented a detailed mathematical model of solar chimney power plant based on Navier-Stokes, continuity and energy equations. The model works in two stages. In the first stage, the solar energy is converted into thermal energy in the solar collector and in the second stage, the generated thermal energy is converted into kinetic energy in the chimney and ultimately into electrical energy using a combination of a wind turbine and a generator. Ho et al. (2011) introduced tools necessary to conduct probabilistic modeling of concentrating solar power plants. Belessiotis et al. (2010) presented theoretically and validated experimentally, a new modeling method based on input-output approach for large solar thermal systems.

Tiwari et al. (2006) Tiwari and Sodha (2007) and Joshi and Tiwari (2007) proposed hybrid photovoltaic hybrid system for air heating applications. Garg et al. (1994), Zondag (2008) and Ibrahim et al. (2011) recommended the hybrid system for water heating applications. It has been observed that PV module temperature varies in the range of 300-325^{o}K for an ambient temperature of 297.5^{o}K. The overall electrical efficiency of the PV module can be increased by increasing the packing factor (PF) and reducing the temperature of the PV module by using the thermal energy associated with the PV module. The carrier of thermal energy associated with the PV module may be either air or water. Once thermal energy withdrawal is integrated with the photovoltaic (PV) module, it is referred as hybrid PV/T system. Dubey and Tiwari (2008) presented a thermal model of a combined system of photovoltaic thermal solar water heater.

1.4.1.2 Solar photovoltaic system

Reliable knowledge and understanding of the PV module performance under different operating conditions is of great importance for correct product selection and accurate prediction of its energy performance. Duffie and Beckman (1991) pointed out that the performance of a crystalline silicon PV module is a function of the physical variables of the PV module material, temperature of PV module and the solar radiance on the PV module surface. Researchers derived various models based on the insolation data, applications and extent of simplicity. Broadly, various models available in literature may be classified into two categories – Empirical models and Analytical models.

a) Empirical Models

The accuracy of solar energy system design depends upon the accuracy of solar radiation data of a particular geographical location. These types of models were developed to estimate the solar radiations. Based on several meteorological parameters (sunshine hours, ambient temperature cloudiness, relative humidity, precipitation and vapor pressure), various empirical formulas have been derived. Sunshine hours, being easily and reliably measured parameter, have been used most commonly for the estimation of solar radiations. The simplest empirical model to predict the monthly average daily global solar radiation on horizontal surface is based on the modified Angström type equation.

$$\frac{H}{H_O} = a + b(\frac{S}{S_O}) \tag{1.1}$$

where, H is the monthly average daily global radiation, H_o is the monthly average daily extraterrestrial radiation, S is the monthly average daily hours of bright sunshine (h), S_o is the monthly average day length (h), and a and b are empirical coefficients (1991).

The monthly average daily extraterrestrial radiation on a horizontal surface (Ho) can be computed from the following equation (1991):

$$H_O = \frac{24}{\pi} I_{SC} (1 + 0.033 \cos(\frac{360D}{365}) \times (\cos\varphi \cos\delta \sin\omega_S + \frac{2\pi\omega_S}{360} \sin\varphi \sin\delta) \qquad (1.2)$$

where, I_{sc} is the solar constant (=1353Wm^{-2}), φ the latitude of the site, δ the solar declination, ω_S the mean sunrise hour angle for the given month and D the number of days of the year starting from first January.

Bakirci (2009) discussed sixty solar radiation empirical models based on sunshine hours. Based on the modifications in Angström type, the sixty models presented were categorized into four groups, that are, linear (Alsaad, 1990; Bahel, 1986; Kholagi et al., 1983) polynomial (Bakirci, 2008; Samuel, 1991; Tahran and Sari, 2005; Tasdemiroglu and Sever, 1991), angular (Dogniaux and Lemoine, 1983; Glover and McGulloch, 1958; Gopinathan, 1988) and other models (Jin et al., 2005; Rensheng et al., 2004; 2006). Perez (1987) presented an empirical model based on diffused solar radiations on tilted surface and ambient temperature. In addition to sunshine hours, day of the year has also been taken as parameter to develop an empirical model (Al-Salaymeh, 2006; Bulut, 2003; 2007; Kaplanis and Kalpani, 2007). Kerr and Cuevas (2003) presented a detailed theoretical analysis and interpretation of the technique proposed to determine the current-voltage characteristics of solar cells based on simultaneously measuring the open circuit voltage as a function of the slowly varying illumination intensity. Radzeimska and Klugmann (2002) presented the influence of temperature on the parameters of silicon photocells. Nishioka et al. (2003) also indicated the importance of temperature characteristics in solar cell development. For engineering applications, many researchers have investigated the simplified simulation models, such as power efficiency models (Jones and Underwood, 2002; Mondol, 2005; Overtraeten and Mertens, 1986; Stamenic et al., 2004; Zhou et al., 2010), which can predict the time series or average performance of a PV array under variable climatic conditions.

b) Analytical Models

This category emerged when solar energy systems are integrated with wind and/ or other energy systems. The power output from solar energy systems are calculated analytically. Karaki et al. (1991) suggested that the performance of individual component is either modeled by deterministic or probabilistic approaches.

i) Deterministic approach

Deterministic methods utilize average or annual values in their analyses, natural oscillations in solar radiations and load demands are not considered. Based on deterministic model, the input energy to PV system i.e. solar radiations and total solar radiations on an inclined surface is estimated as:

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{1.3}$$

where, I_b and I_d are direct and diffuse solar radiations, R_d and R_r are the tilt factors for the diffuse and reflected part of the solar radiations (Duffie and Beckman, 1991). Hourly power output from PV system with an area A_{PV} (m^2) on an average day of j^{th} month, when total solar radiation of I_T (kWh/m^2) is incident on PV surface, is given by (Markvart, 2000);

$$P_{PV} = I_{Tj} \eta A_{PV} \tag{1.4}$$

where, system efficiency η is given by (Habib et al., 1999);

$$\eta = \eta_m \eta_{PC} P_f \tag{1.5}$$

and the module efficiency η_m is given by

$$\eta_m = \eta_r [1 - \beta(T_c - T_r)] \tag{1.6}$$

where, η_r is the module reference efficiency, η_{PC} is the power conditioning efficiency, P_f is the packing factor, β is the array efficiency temperature coefficient, T_r is the reference temperature for the cell efficiency and T_c is the monthly average cell temperature and can be calculated as follows (Kohle et al., 2003):

$$T_c = T_a + \frac{\alpha\tau}{U_L} I_T \tag{1.7}$$

where, T_a is the instantaneous ambient temperature, $U_L / \alpha\tau = I_{T, NOCT} / (NOCT - T_{a,NOCT})$, and NOCT is normal operating cell temperature, $T_{a, NOCT} = 20^{o}C$ and $I_{T, NOCT} = 800 W/m^2$, for a wind speed of 1m/s.

Notton et al. (1996) defined a dimensionless term “solar contribution” to model the power output from solar energy systems. Solar Contribution (SC) is the ratio of the load supplied by the PV system during a given period T to the total load during the same period and is given by (Notton et al., 1996).

$$SC = 1 - \left| \frac{DE(T)}{L} \right| \tag{1.8}$$

where, DE(T) : energy deficit during the time period T; L : total load during the time period T.

Hefnawi (1998) calculated the peak power output from PV array as,

$$P_{PV} = \{E_L + (E_L \times D / C_R \times B_E) \times 100\} / X \tag{1.9}$$

where, P_{PV} : the array size in peak watts ; E_L : the daily energy requirement in Wh/day ; D : the required number of storage days ; C_R : the charge recovery of the battery days ; B_E : the watt-hour efficiency of the battery ; and X: the annual average equivalent peak hours/day (sunshine period). Alamsyah et al. (2004) presented a simplified model for estimating energy from PV system.

ii) Probabilistic approach

Many studies have proved that cloudiness is the main factor affecting the difference between the values of solar radiation measured outside the atmosphere and on earthly surface. To consider cloudiness, a daily clearness index K_t has been defined as the ratio of a particular day's total solar radiation, H_t to the total extra-terrestrial solar radiation, H_o for that day, both referred to a horizontal surface. Also, hourly clearness index k_t can be defined as the ratio of the irradiance on a horizontal plane, I_t to the extra terrestrial solar irradiance, I_o. Based on probabilistic model, Kroposki et al. (1994) mentioned the above power equation as,

$$P_{PV} = A_{PV}.\eta.(T.k_t - T'k_t^2) \tag{1.10}$$

where, T and T' are the parameters that depend on inclination β, declination δ, reflectance of the ground ρ, latitude φ, hour angle ω, sunset hour angle ω_s and day of the year n.

As per Papoulis (1982), if the probability density function $f_{k_t}(k_t)$ for the random variable k_t is known, it is possible to obtain the probability density function $f_{P_{PV}}(P_{PV})$ for P_{PV} by applying the fundamental theorem for function of a random variable. Taking the probability function as proposed by Hollands and Huget (1983), the probability density function for P_{PV} when T >0 and T'<0 can be written as (1990)

$$f_{P_{PV}}(P_{PV}) = \begin{cases} \dfrac{c.(k_{tu} - 1/2(\alpha + \alpha'))}{k_{tu.} A_{PV} .\eta.T'.\alpha'} .l^{\frac{\lambda}{2}(\alpha+\alpha')} ; if P_{PV} \in [0, P_{PV}(k_{tu})] \\ 0; otherwise \end{cases} \tag{1.11}$$

where, $$\alpha = \frac{T}{T'} and \alpha' = \sqrt{\alpha^2 - 4.\frac{P_{PV}}{\eta.T'.A_{PV}}}$$

where, k_{tu} is the upper bound for k_t; c, λ is parameters of the probability density function of P_{PV}.

Cabral et al. (2010) performed a comparative study of deterministic and stochastic sizing of standalone photovoltaic systems, analyzing both the stochastic model for solar radiation, as well as the Loss of Power Supply Probability (LPSP), with the objective of verifying the best method for photovoltaic system modeling. Villalva et al. (2009) presented a comprehensive modeling approach to describe solar cell based on its one-diode model equivalent circuit. Meyer and Dyk (2000) developed an energy model based on regression analysis of total daily irradiation and maximum daily ambient temperature. Bhuiyan et al. (2000) studied the feasibility of standalone photovoltaic power system in remote and rural areas of Bangladesh.

c). Time Series Modeling

A time series is a collection of time sequence observations a_t, recorded at a specific time (Faraway and Chatfield, 1996). Time series modeling is a conditional expectation but the computation of the conditional expectation requires knowledge of the joint probability of the past and the current samples (Rizvi et al., 1996).

Time series data of resources is required for the reliable operation of the sources and thereby, the sufficient utilization of resources. In renewable energy domain, time series modeling implies the development of such a model which represents a set of time ordered observations recorded at a specific time. There are various techniques to develop the time series model of solar and wind energy resources. These techniques are broadly classified into four different categories which are as follows:

i) Numeric Weather Prediction (NWP) Methods.
ii) Statistical Methods.
iii) Methods based on ANN.
iv) Hybrid Approaches.

NWP methods are used to develop physical models using the actual meteorological data for wind speed forecasting (Jing-Shan, 2003; Landberg, 1998). The limitation of NWP models is their complexity which limits their utility to on-line and very short term operation of power systems. Statistical and ANN based methods are based on the previous historical data. Statistical methods require a pre-defined mathematical model and they use the difference between the predicted and the actual quantity to tune the model. ANN based methods learn the input and output relationships in a non-statistical manner. Statistical techniques are based on simplifying statistical assumptions about the measured data, which are not always true. ANN based methods presents a solution to this problem as these techniques are based on the training and therefore, no statistical assumptions are needed. As far as hybrid approaches are concerned, they are the combination of –physical and statistical approaches; short term and medium term prediction and/or alternative statistical approaches (Yuan-Kang and Jing-Shan, 2007).

ANN based techniques are becoming more and more popular in renewable energy domain (Mellit et al., 2004; 2005; 2009). Table 1.8 presents a brief description of different techniques found in literature.

Table 1.8: List of different techniques

Approach	**Technique**	**Reference**
Statistical	Auto-Regression (AR)	(Aguiar and Pereira, 1992; Hokoi et al., 1990; Knight et al., 1991; Maafi and Adane, 1989)
	Auto-Regression & Moving Average (ARMA)	(Lopez and Cardona, 1998)
	Auto-Regression Integrated Moving Average (ARIMA)	(Hamilton, 1994)
	Bayesian Inferences	(Census of India; Diday et al., 1982; Pole et al., 1994)
Probabilistic	Markov Chains Markov Transition Matrix (MTM)	(Amato et al., 1996; Lofoget et al., 2000; Muselli et al., 2001)
Analytical	To develop a set of differential equations or parameterized expressions	(Weigend et al., 1990)
Empirical	To develop empirical regularities or periodicities during the observation of the dynamic process	(Cichocki and Unbehauen, 1993; Farmer and Sidorowich, 1988)

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Fourier	Fourier series	(Carson, 1963; El-Shal and Mayhoub, 1995; Lamba and Khambte, 1991)
Learning Based	k-Nearest Neighbors (k-NN)	(Sharif and Burn, 2006; Yakowitz, 1987)
	ANN	(Al-Alawi et al., 1998; Charaborty et al., 1992; Kalogirou et al., 2002; Mohandes et al., 2000; Patil and Krishnaprasad, 1993)

The classical techniques like ARMA and Bayesian Inferences are widely used in predicting the solar and wind energy resources. The scope of these statistical techniques is limited to linear regression applications. Autoregressive stochastic models are incapable of simulating the nonlinear nature of various dynamic processes of the real world.

ANN based techniques presented themselves as an alternative to tackle complex and ill-defined problems which is generally the case with solar and wind energy resource modeling. A comparison of ANN based techniques with others have been presented in the Table 1.9.

Table 1.9: Comparison of statistical and ANN based techniques

Attribute	**Statistical**	**ANN**
Data Requirement	Detailed	Light
Problem Definition Requirement	Strict	Light
Problem Handling Requirement	Strict	Light

ANN based techniques are well suited for solar and wind energy resource modeling as at many stations around the world, the data is not available. Secondly, these sources being intermittent so it is difficult to obtain a direct correlation between the data points and in addition, the obtained correlations are complex and non-linear sometimes. The limited problem definition and problem handling requirements of statistical and other approaches restrict their scope for these types of problems.

Solar energy modeling, in general, gives a relationship between the solar radiations (global or diffused) on a horizontal surface and the meteorological variables such as ambient temperature, relative humidity, sunshine hours etc. Various linear and non-linear models are discussed (Bakirci, 2009). With the advent of ANN based techniques in renewable energy domain, the deficiency of data availability as well as the complexity of various models has been overcome in solar energy modeling.

Mohandes et al. (1998) presented a neural network technique to estimate the solar radiations in the Kingdom of Saudi Arabia. Back-propagation technique is used to train the multi-layer feed-forward network. The solar radiation from some stations was collected to train the network and data from some stations were used to test the model.

Alawi and Hinai (1998) presented a novel approach for the prediction of solar radiations using artificial neural network. The various climatological parameters were used to predict the global solar radiations. Feed-forward network has been used to develop the model. Mihalakakou et al. (2000) describes a neural network for the prediction of future hourly solar radiations using the past values. Feed-forward network with back-propagation technique has been used for forecasting. Future values of hourly total solar radiation times series based on their past values have been simulated.

Dorvio et al. (2000) discussed a radial basis function (RBF) based neural network for the estimation of solar radiations by first estimating clearness index. The RBF based network was preferred over multi-layer perceptron (MLP) because of less computing power requirements. Sozen et al. (2004) determined the solar energy potential using artificial neural network. Scaled conjugate gradient, Pola Ribiere conjugate gradient and Lavenberg-Marquardt learning algorithms and a logistic sigmoid transfer function were used in the network.

Fadare (2009) also developed an artificial neural network for the solar energy potential in Nigeria. Standard multi-layered, feed forward, back propagation neural networks with different architectures have been designed with meteorological data as the inputs and the total solar radiations as the output. Lam et al. (2008) predicted daily global solar radiations using measured sunshine duration for 40 cities covering different climatic zones and sub-zones of China. The coefficient of regression for all the cities was found to be 0.82 and higher which validates the model for prediction.

Reddy and Ranjan (2003) developed an artificial neural network model for the prediction of daily as well as hourly global solar radiations. The values obtained are found in good agreement with the actual values. This model has also been compared with the available regression models and was found superior than those models in terms of mean square error.

Benghanem and Mellit (2010) developed a model for predicting the daily global solar radiations using meteorological parameters as input. RBF network has been used to develop the model. The developed models very well complied with the actual data as the regression coefficient was found to be higher than 0.8. Khatib et al. (2011) predicted the global solar radiations for Malaysia. They used the multi-layer perceptron for the development of the neural network model. Hontoria et al. (2005) applied the multi-layer perceptron based neural network to develop the solar radiation maps for Spain. The methodology developed the shortcomings of non-availability and/or consistency of data for certain points on the map.

Elminir et al. (2007) again utilized artificial neural network to predict the diffused fraction of daily and hourly solar radiations. With this model, the short-coming of the non-existence of records of diffuse radiations for most of the locations of Egypt has been tried to overcome through artificial neural network. The results obtained from ANN model were found to be more suitable than the regression models. Elizondo et al. (1994) developed a neural network to predict the daily total solar radiations as a function of readily available weather data and other environmental variable. The developed model was found to be useful for estimating daily solar radiations in cases where only daily maximum and minimum air temperature and precipitation are available.

Alam et al. (2006) presented a neural network to predict the beam solar radiations with reference clearness index as the input parameter. Feed-forward back-propagation algorithm has been used to develop the model. The values obtained were found to be comparable with the actual values as the mean square error was vey less. Kemmoku et al. (1999) predicted the insolation level through a multi-stage neural network. The objective of using the multi-stage neural network was to minimize the mean square error which is quite higher ion case of single stage neural network. The network defined in this study was of three stages. In the first stage, the average atmospheric pressure has been forecasted from the previous day values. In the second stage, the insolation level has been predicted using the average atmospheric pressure and the weather data. And, in the third stage, the insolation level for next day has been predicted using the insolation level and other weather data.

Mohandes et al. (2000) utilized the RBF technique to estimate the monthly mean daily solar radiations. The performance of the RBF network has also been compared with multi-layer perceptrons network and a classical regression model. The RBF network was foundto be viable. Kalagirou et al. (2013) presented a multi-layer recurrent network for the prediction of daily solar radiations. The standard back-propagation algorithm has been used for the training purposes. Various meteorological parameters have been used as the input. The model was found viable with lesser mean square error values.

Hacauglu et al. (2008) studied a year's hourly solar radiation data and formed an image model for forecasting. A 2-D forecasting performance has been tested through feed-forward neural networks using the same data. It was found that the neural network models are better in forecasting as compared with 1-D and 2-D linear prediction filters.

1.4.2 Wind energy system

Wind energy is another clean and free renewable energy source. Detailed analysis of wind data is a prerequisite for the estimation of wind energy potential and for the design of efficient wind energy conversion system. Ackermann and Soder (2000) and Herbert et al. (2007) presented a review on wind energy technologies. The hour by hour simulation programs have been the main tools to determine the long-term performance of wind energy system. Bansal et al. (2002) discussed the design aspects of wind energy conversion systems. Sopian et al. (1995) emphasized the utilization of wind energy system and discussed the potential of wind energy in Malaysia.

a) Analytical Models

i) Deterministic approach

Generally, for a typical wind turbine, the power output characteristic can be assumed in such a way that it starts power generation at the cut-in wind speed, then the power output increases linearly as the wind speed increases from the cut-in speed to the rated wind speed, and the rated power is produced when the wind speed varies from the rated wind speed to the cut-out wind speed at which the wind turbine will be shut down for safety considerations. Nehrir et al. (2000) presented the calculation of wind turbine power based on electrical load, average wind speed and power curve of the wind turbine. Based on the above assumptions, Fadia et al. (1997) described the most simplified model to simulate the power output of a wind turbine. Mathematically, the wind turbine characteristics can be represented as (Chedid et al., 1998):

$$P_w = 0 \qquad v_c < v_{ci}, \tag{1.12}$$

$$P_w = a\,V^3 - b\,P_r \qquad v_{ci} < v < v_r, \tag{1.13}$$

$$P_w = P_r \qquad v_r < v < v_{co} \tag{1.14}$$

$$P_w = 0 \qquad v > v_{co} \tag{1.15}$$

where, $a = P_r / (v_r^3 - v_{ci}^3)$, $b = v_{ci}^3 / (v_r^3 - v_{ci}^3)$, P_r is the rated power, v_{ci}, v_{co} and v_r are the cut-in, cut-out and rated speed of the wind turbine. Actual power available from wind turbine is given by Chedid et al., (1998),

$$P = P_W\,A_W\,\eta \tag{1.16}$$

where, A_w is the total swept area, η is efficiency of wind turbine generator and corresponding converters. A model of wind speed variation with height is also required in wind energy applications. Generally two approaches can be used to model the vertical profile of wind speed over regions of homogeneous flat terrains. The first approach is the log-law and the second approach is power-law which is widely used by the researchers. Wind speed at hub height can be calculated by using power-law equation (Patel, 1999):

$$v_z = v_i \left(\frac{z}{z_i} \right)^x \tag{1.17}$$

where v_Z and v_i are the wind speed at hub and reference height Z and Z_i, and x is power law exponent and is generally taken as 1/7. Ai et al. (2003) used a deterministic approach to design a PV-wind based hybrid energy systems. Different empirical elations have been used to determine the hourly output from solar as well as wind energy systems. Diaf et al. (2008) presented a simplified deterministic approach for the modeling of solar as well as wind energy resources in a hybrid system. For estimating the solar power output, the solar radiation available on the module surface, the ambient temperature and the manufacturer's data for PV module have been used as inputs. Similarly for wind turbine power output, the wind turbine characteristic equation has been used. Yang et al. (2003), Kanase-Patil et al. (2010), Dufo-Lopez et al. (2005) and Yang et al. (2007) also discussed some simplified deterministic approach for the mathematical modeling of the renewable energy resources.

ii) Probabilistic approach

Since the calculation based on actual wind speed and direction is time-consuming and sometimes impossible, average wind speed can be used. Muljadi and Butterfield (2001) pointed out that the wind turbine power curves cannot exactly represent wind turbine power output because the curves can only give the power output of the wind turbine as a function of the average wind speed ignoring instantaneous wind speed variations, and thereby will, to some extent, undermine the performance of the wind turbine.

Since the wind speed is a random variable, a long-term meteorological data is desirable to describe wind energy potential of the sites. In order to account the variability of the wind speed during the j^{th} hour (j = 1,2,…24) of the m^{th} month (m = 1,2,…….12), it is characterized by Weilbull distribution with scale parameter, α_w and a shape parameter, β_w. Weilbull two parameter density functions is widely accepted for evaluating local wind load probabilities and can be seen as standard approach. Density and distribution functions are given by;

$$f_v(v) = \frac{\beta_w}{\alpha_w^{\beta_w}}.v^{(\beta_w - 1)}.\exp\left(-\left(\frac{v}{\alpha_w}\right)\right)^{\beta_w} \qquad (1.18)$$

$$F_v(v) = 1 - \exp\left(-\left(\frac{v}{\alpha_w}\right)\right)^{\beta_w} \qquad (1.19)$$

Based on the above equations, the probability density function $f_{P_w}(P_w)$ for the power output of the wind energy conversion system can be obtained using the above equations by the application of the transformation theorem described by Abouzahr and Ramakumar (1993) as given below;

$$f_{P_w}(P_w) = \begin{cases} F_1 ; P_w = 0 \\ \left(\frac{V_r - V_{ci}}{P_r}\right).\left(\frac{\beta_w}{\alpha_w^{\beta_w}}\right) \times [V_{ci} + (V_r - V_{ci}).\frac{P_w}{P_r}]^{(\beta_w - 1)} \times \exp\left(-\left(\frac{V_{ci} + (V_r - V_{ci}).\frac{P_w}{P_r}}{\alpha_w}\right)^{\beta_w}\right) ; 0 < P_w < P_r \\ F_2 ; P_w = P_r \end{cases} \qquad (1.20)$$

where,

$$F_1 = 1 - [F_v(V_{co}) - F_v(V_{ci})]$$

$$F_2 = F_v(V_{co}) - F_v(V_r)$$

Weisser (2003) estimated the wind energy using Weilbull density function for Grenada. Besides Weibull distribution, inverse Chi square distribution can also be used to describe wind energy data with a considerable degree of accuracy. Panda et al. (1990) presented a probabilistic model for the wind data and used Box-Cox transformation to transform the data to a normal distribution. Torre et al. (2001) proposed Markovian model for studying wind speed time series in Corsica because a stochastic model like a Markov chain seems to be more accurate. Ulgen et al. (1990) studied the wind variation for a typical site using Weilbull distribution and Rayleigh distribution was found suitable to represent the actual probability of wind speed data for the site studied.

In other studies, Borowy and Salameh (1994) and Karaki (1999) applied probabilistic models considering Weilbull shape parameter β_w. Additionally, Alhusein et al. (1993) and Lu and Yang (20000) described quadratic expression models for the simulation of power output of wind turbines.

It is a well known fact that solar and wind energy resources are of fluctuating nature and are, furthermore, "of use it or lose it" character. Modeling of solar and wind energy resources is in itself an exhaustive task. The main challenge is to replicate the real time conditions in the model developed. There is always a trade-off between the accuracy and the complexity of the model. The biggest drawback, in most of the cases, is the detailed and accurate data (solar radiations and wind speed) availability.

In addition to empirical models, analytical models are the most commonly used models. On the basis of utilization of available data, the analytical models may be categorized into deterministic and probabilistic approaches.

Perez et al. (1987) presented a simpler method for the determination of diffused radiations. The model presented was used to estimate the short time step irradiance on titled planes based on global and direct radiations. Habib et al. (1999) considered a deterministic approach for the determination of power output from solar as well as wind energy resources. The hourly insolation and wind speed data has been taken to calculate the average power output from the resources.

Kolhe et al. (2003) proposed an analytical model for estimating the performance of the solar-wind stand-alone system. The solar radiations have been obtained from the available empirical relations to determine the performance of the solar energy system. Similarly, wind power output has been determined through the specified turbine characteristics. Notton et al. (1996) presented an approach based on the energy deficit and wasted energy to determine the solar energy contribution and excess energy. Optimum solar contribution has been evaluated in a system comprising of solar with fuel generator. El-Hafnawi (1998) presented a sizing method for a solar-diesel hybrid system with battery storage. The sizing has been done on the basis of number of storage days and maximum depth of discharge. The power output from solar system has been directly determined using daily energy requirement, required number of storage days, the charge recovery of the battery days, the watt-hour efficiency of the battery and the annual average peak hours per day. Nehrir et al. (2000) developed a computer program for evaluating the performance of a solar-wind stand-alone system. The steady state models of solar, wind and other components have been used in this study.

Probabilistic approach has been presented by Borowy and Salameh (1994) for the determination of hourly power output from solar and wind energy resources. The probability distribution function has been evaluated for each hour of a typical day in every month. Once the distribution functions are known, the average power output for every hour of the typical day in each month can be easily calculated by integrating the distribution function. Karaki et al. (1999; 2000) applied probabilistic approach to estimate the power output from solar as well as wind energy resources. The probability of hardware failure has also been taken into account. The entire time period was divided into time segments and it has been assumed that during that time segment, the insolation/wind speed would follow the Beta/Weilbull distribution function respectively.

Fadia et al. (1997) used probabilistic technique to analyze solar wind based hybrid system. The load is assumed to follow uniform probability distribution and the loss of power supply probability has been selected to obtain the optimum sizes of the system. Abouzahr and Ramakumar (1993) presented a probabilistic approach based on convolution technique to analyze the performance of a grid connected wind energy conversion system. The power injected into the grid was considered to be a continuous random variable. Its probability density function has been obtained through the convolution of the function of wind speed and load. Borowy and Salameh again (1996) utilized the probability based approach for determining the optimum sizing of a solar-wind based hybrid system. Long term data has been used to determine the probability density functions for wind speed and solar irradiance.

Depending upon the extent of accuracy required the monthly, daily, hourly or minute base average value of solar radiations and/ or wind speed may be taken. The limitation of the data un-availability, to such a detailed level, paved way for the probabilistic approach. In probabilistic approach, the time frame is divided into segments and for each segment, probability density function is formulated. This formulation approach, to an extent, overcomes the data un-availability limitation.

b) Time Series Modeling

Wind energy modeling, in general, gives a relationship between the wind speeds and the variables such as mast height, ambient temperature, etc. Fonte and Quadrado (2005) developed an ANN based model to predict the average hourly wind speed. A multi-layer perceptron with feed forward architecture and back propagation algorithm for training was used to develop the model. Hayashi and Kermanshahi (2014) developed a multi-layer feed forward neural network for the prediction of wind speed and the power output from the wind energy. The model based on the neural network demonstrated a good agreement and produced the wind forecast with the accuracy of 90% and above.

Kariniotakis et al. (1996) presented a recurrent high order neural network to predict the power output profile from a wind farm. It was found that the developed model performed better than the existing persistence and the classical models. Rohrig and Lange (2006) studied the German scenario for wind power prediction. It was conveyed in the study that quite accurate methods for current and expected wind power prediction methods are developed and implemented in various stations of the transmission system operators.

Alexiadis et al. (1999) developed an ANN based forecasting model to predict the wind speed and power output several hours ahead. The method is then tested for different sites and was found accurate in forecasting as compared with persistence forecasting models. Gnana Sheela and Deepa (2012) presented a RBF based neural network to develop an efficient computing model for wind speed prediction. The mean square error of prediction is found much lesser than that from standard feed forward neural network with back-propagation algorithm.

Chen et al. (2009) developed a RBF based neural network for wind power forecast. The architecture of RBF network has been constructed through orthogonal least squares and cultural algorithms. These algorithms were used to tune the parameters of the RBF network. Sideratos and Hatziargyriou (2007) compared two statistical models for short term wind power forecasting. These two methods included the numerical weather prediction estimator models based on fuzzy logic and wind power forecasting models using neural network combinations. Table 1.10 presents a summary of review work in energy modeling by ANN based techniques with the input variables considered in the study.

Table 1.10: Different Neural Networks with training algorithms and input variables

Network	**Training Algorithm**	**Input**	**Reference**
Multi-Layer Feed Forward	Back-Propagation	Latitude, Longitude, Altitude, Sunshine Duration	(Mohandes et al., 2000)
Multi-Layer Feed Forward	Back-Propagation	Location, Month, Mean pressure, Temperature, Vapor pressure, Relative humidity and Sunshine duration	(Alawi and Hinai, 1998)
Multi-Layer Feed Forward	Back-Propagation	Global Radiations	(Mihalakakou et al., 2000)
Multi-Layer Recurrent	Back-Propagation	Month, Day of Month, Julian day, Season, Mean Ambient Temperature and Mean Relative Humidity	(Dorvio et al., 2008)

Contd….

Feed Forward	Scaled Conjugate Gradient, Pola-Ribiere Conjugate Gradient, Levenberg–Marquardt learning algorithm	Latitude, Longitude, Sunshine ratio, Temperature, Month	(Sozen et al., 2004)
Multi-Layered Feed Forward Neural Network	Back Propagation	Latitude, Longitude, Sunshine Hours, Altitude, Month, Temperature, Relative Humidity	(Fadare et al., 2009)
Multi-Layer Feed Forward	Back Propagation	Latitude, Longitude, Sunshine Hours, Altitude, Day Number, Temperature, Relative Humidity	(Lam et al., 2008)
Multi-Layer Feed Forward	Back-Propagation	Latitude, Longitude, Sunshine Hours, Altitude, Month, Time, Temperature, Relative Humidity, Wind speed, rainfall	(Reddy and Ranjan, 2008)
Radial Basis Function (RBF)		Temperature, Relative Humidity, Sunshine Hours	(Benghanem and Mellit, 2010)
Feed Forward Multi-Layer Perceptron (MLP)	Back-Propagation	Latitude, Longitude, Sunshine Hours, Altitude, Day Number,	(Khatib et al., 2011)
MLP	Back-Propagation	Hourly Irradiation values	(Hontoria et al., 2005)
MLP	Back-Propagation	Hour, Day, Month, Year, Global radiations, Hourly extra-terrestrial radiations	(Elminir et al., 2007)
MLP	Back-Propagation	Latitude, Longitude, Altitude, Month, Sunshine Ratio, Rainfall and Humidity	(Elizondo et al., 1996)

Contd….

Feed Forward	Back-Propagation	Temperature, Precipitation, Clear-sky radiation, Day length and Day of the year	(Alam et al., 2006)
Single and Multi-stage	Back-Propagation	Atmospheric Pressure, Insolation and Temperature	(Kemmoku et al., 1999)
RBF	Modified Interpolation Function	Latitude, Longitude, Altitude and Sunshine duration	(Mohandes et al., 2000)
Recurrent Neural Network	Back-Propagation	Relative Humidity and Temperature	(Kalogirou et al., 2002)
Feed Forward	Back-Propagation & others	Insolation	(Hacouglu et al., 2008)
MLP	Back-Propagation	Wind Speed	(Fonte and Quadrado, 2005)
Recurrent	Back-Propagation	Air Pressure, Temperature, Humidity, Time	(Hayashi and Kermanshahi, 2014)
Recurrent	Back-Propagation	Wind Speed	(Kariniotakis et al., 1996)
Feed-Forward	Back-Propagation	Air Pressure, Temperature	(Rohrig and Lange, 2006)
MLP	Back-Propagation	Wind speed and wind direction	(Alexiadis et al., 1999)
RBF	Gradient Descent	Temperature, Humidity, Wind gust, Wind speed	(GnanaSheela and Deepa, 2012)
RBF	Orthogonal Least Square and Culture Algorithm	Wind speed	Chen et al. 2009)
RBF	Gradient Descent	Wind speed, Direction, Wind power	(Sideratos and Hatziargyriou, 2007)

While comparing ANN models with other models, the average values of Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE) and Mean Bias Error (MBE) for the global solar energy model are give in Table 1.11 (Khatib et al., 2011). This table clearly advocates the superiority of ANN models over other models.

Among different networks in ANN modeling techniques, it is quite clear that the multi-layer feed forward with back-propagation training algorithm is the most popular network.

Table 1.11: Average Error values for different models

	MAPE	**RMSE**	**MBE**
Linear Model	8.13	0.44	-0.014
Nonlinear Model	6.93	0.41	-0.013
Fuzzy logic model	6.71	0.42	0.019
ANN model	5.38	0.35	-0.019

As far as different network models are concerned, RBF has certain advantages over traditional MLP like in RBF network, solution of clustering problem can be performed independently, also, output in scarcely trained input is not random in RBF (Leonard et al., 1992).

Back-Propagation is one of the most powerful learning algorithms in neural networks (Kalogirou et al., 2001). The disadvantage with BP algorithm is its slow convergence. Among other training algorithm, Levenberg-Marquardt (LM) is observed to produce more accurate results in terms of lower RMSE (Hacouglu et al., 2008).

1.4.3 Biomass/Biogas System

Biomass is one of the primary sources of energy. Fig. 1.4 gives a snapshot of the different processes involve in different biomass conversion technologies (Ferreira et al., 2009). Approximately, two thirds of biomass is used for cooking and heating in developing countries (IEA, 2006). Biomass burning cook stoves are being used in rural areas which cause health problems, especially to women and children who are exposed to smoke emissions. This pointed to the need to develop fuel efficient wood burning stoves so as to improve health and hygienic conditions, reduce drudgery of women, and reducing fuel consumption leads to protection of forests and environment. Narayanan and Natarajan (2007) have also studied the firing of blends of coal and biomass in cook stoves for domestic cooking. Aggarwal and Chandel (2004) presented a review on improved cook stove programme in western Himalayan state of India.

In the last three decades gasification of biomass for decentralized power generation, water pumping as well as thermal applications have received considerable attention of planners, researchers, entrepreneurs, etc all around the globe. This resulted in the vast development in the area of biomass gasification technology. As per MNRE report (1996), 5hp and 10hp biomass gasifier systems for water pumping, 17.5kWth (15000kcal/hr) to 291 kWth (250,000kcal/hr) systems for thermal applications, and 3-500kWe systems for power generation are now commercially available in India.

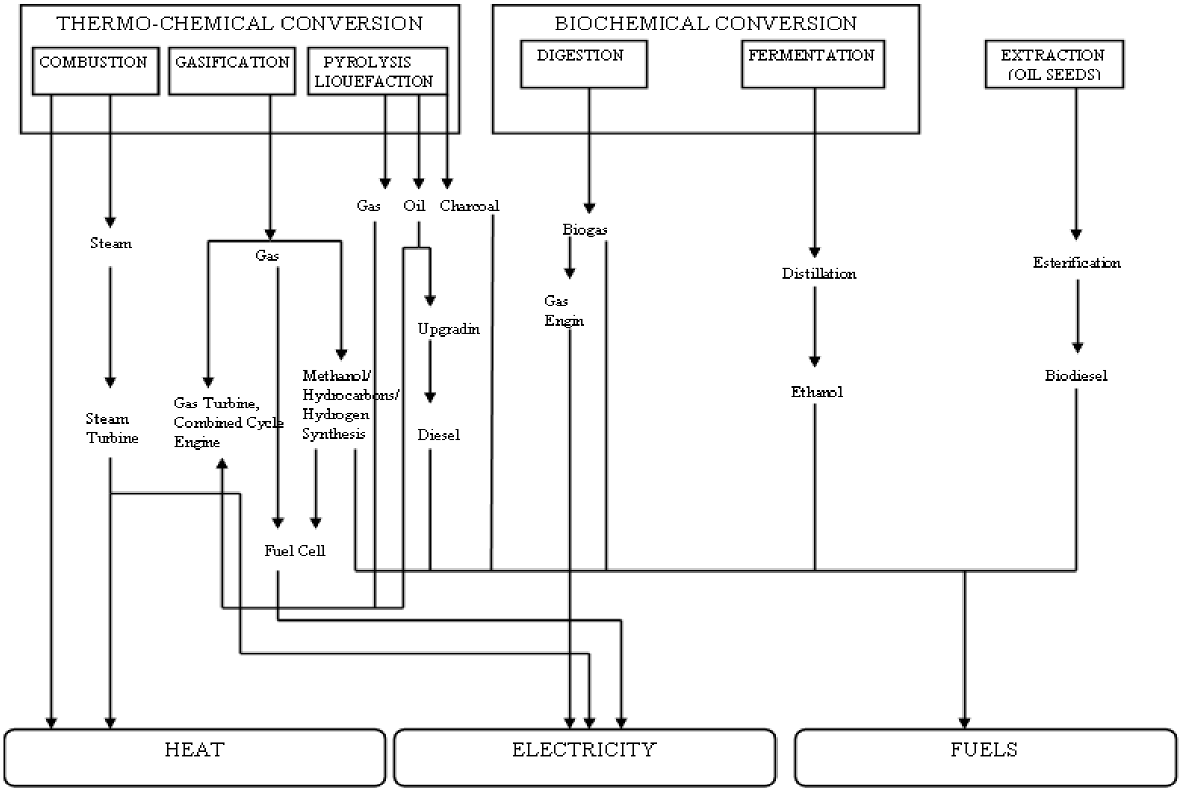


Fig 1.4: Biomass Conversion Technologies (Ferreira and Moeiza, 2009)

Analysis of the economics of the gasifier system has been done by several authors. Tripathi et al. (1999) performed a financial evaluation and calculated the unit cost of thermal energy for biomass gasifier based institutional cooking systems. As far as conversion of biomass to electricity is concerned, there are six possible technologies as depicted in Table 1.12. Tiwari et al. (1992; 1996) discussed the certain factors of biogas production along with design criteria for biogas plant and they also determined the period for biogas production.

The measures of the economic feasibility of the biomass gasifier for decentralized power generation are: (i) the levelised unit cost of electricity (LUCE) produced by the gasifier in comparison to diesel generator (ii) the breakeven analysis (i.e. comparison of diesel price, for which the gasifier is feasible with the prevalent market price of diesel). Besides the capital cost, several other factors influence the cost of power generation. These are: (i) specific fuel consumption (at full or part loads) (ii) Capacity utilization factor (iii) useful life of gasifier and generator, lastly (iv) the unit price of biomass and supplementary fuel, i.e. diesel. A complete review on biomass in Indian context is presented by Buragohain (2010).

Table 1.12: Biomass to Electricity Conversion Technologies (Buragohain et al., 2010)

S. No.	Technology	Efficiency	Relative capital cost per kW	Merits	Limitations
1.	Gasifier with generator coupled to IC engine	15-22%	1.0	Low cost and simple construction	High maintenance for engine, fuel specificity suitable for size upto 250kW.
2.	Biomass boiler steam engine	<10%	1.5-2.0	Robust design, biomass flexibility, low maintenance cost	Low efficiency, not suitable for installation and operation in rural and remote areas.
3.	Biomass boiler steam turbine	15-24%	1.1-1.3	Robust design, biomass flexibility, relatively high efficiency	Economically feasible for capacity of about 5 MW or higher; thus, unsuitable for small to medium-scale application for remote rural areas.
4.	BIGCC (Biomass Integrated Gasification Combined Cycle) with either steam or gas turbine	45-55%	2.0-3.0	High efficiency	Complex design, yet to be demonstrated for biomass (under R&D)
5.	Biomethanation followed by IC engine (with methane)	20-25%	Under R&D	Low engine maintenance due to purer and cleaner gas, simple design, construction and operation	Yet to be demonstrated (under R&D)
6.	External combustion engines	20-30%	1.5-2.0	Flexibility in biomass, high efficiency	Yet to be demonstrated (under R&D)

1.4 OPTIMIZATION OF INTEGRATED RENEWABLE ENERGY SYSTEMS

1.4.1 Criteria for IRES Optimization

Most of the renewable energy resources are of a fluctuating or intermittent in nature. Such systems may be designed from an economic perspective or from a techno-operational perspective; but within these two categories there are sub-divisions. Economic optimization criteria include total energy systems costs, capacity costs and societal costs. From a techno-operational perspective, optimization criteria include fuel savings, CO_2 emissions, reserve backup capacity, elimination of excess power generation and generation at minimum reliability. Diaf et al. (2008) studied the techno-economic optimization of a stand-alone hybrid PV/wind system in Corsica Island. Many researchers have carried out the evaluation on the basis of power reliability and system life-cycle cost. An optimum combination can make the best compromise between the two considered objectives as power reliability and system cost.

There are a number of methods used to calculate the reliability of the integrated systems. Yang and Burnett (2003) suggested that the most popular method is the loss of power supply probability (LPSP) method. Al-Ashwal and Moghram (1997) defined the LPSP as the probability that an insufficient power supply results when the system is not able to satisfy the load demand. Two approaches exist for the application of the LPSP in designing a stand-alone system. The first one is the chronological simulations. This approach is computationally burdensome and requires the availability data spanning a certain period of time. The second approach uses probabilistic techniques to incorporate the fluctuating nature of the resource and the load, thus eliminating the need for time series data. Some other power reliability criteria also exist, such as Loss of Load Probability (LOLP), System Performance Level (SPL), Loss of Load Risk (LOLH) and Expected Energy Not Supplied (EENS). Maghraby et al. (2002) presented a method based on LOLR to decide an optimum proportion of the solar and wind energy in a hybrid system. Shrestha and Goel (1998) defined the SPL as the probability that the load cannot be satisfied. Ostergaard (2009) reviewed the optimization criteria and suggested that both the SPL and LOLH methods are widely used. Kanse-Patil et al (2010) presented a method based on EENS.

A number of economic criteria were discussed such as the Net Present Cost, Levelised Cost of Energy and Life Cycle Cost. The Net Present Cost is defined as the total present value of a time series of cash flows, which includes the initial cost of all the system components, the cost of any component replacements that occur within the project lifetime and the cost of maintenance. The system lifetime is usually considered to be the life of the PV modules, which are the elements that have a longer lifespan. Dufo-Lopez et al (2005) described the detailed calculation and also suggested that some cost depend on the control strategy selected amongst those possibilities. Deshmukh and Deshmukh (2008) suggested that levelised cost of energy has been extensively used as an objective term to evaluate the hybrid solar-wind system configurations. Yang et al. (2007) suggested levelised cost of system as an economic approach and similarly, Valente and Almeida (1998) suggested life cycle cost approach. These approaches are widely used.

Researchers have given due importance to the environmental concerns in their optimization problem. Soroudi et al (2011) suggested emission reduction as an objective besides, cost factor. Singh et al (1996) considered five different objectives to select the best plan for small, medium and large farms in Punjab. The objectives were of – minimization of energy input, maximization of gross returns, minimization of capital borrowing, minimization of labor hiring and minimization of risk for the availability of energy inputs. Naresh and Sharma (2000) considered the objectives of maximization of hydropower generation and satisfaction of irrigation requirements as far as possible. Haralambopoulos and Polatidis (2003) described an applicable group decision making framework for assisting with multi criteria analysis in renewable energy projects. The authors considered three quantitative criteria – conventional energy saved (toe/yr), return of investment and number of jobs created and the other two criteria were qualitative –environmental pressures and entrepreneurial risk of investment.

1.4.2 Optimization Techniques

Many researchers proposed optimization methods for solving problems found in renewable energy systems. Optimization methods may be classified on the basis of number of objectives – Single Objective Optimization Method (SOOM) and Multi Objective Optimization Method (MOOM). Various techniques based on SOOM have been applied by the researchers to solve the renewable energy problem. Due to investment costs of creating a renewable energy structure, the primary interest from the point of view of the design and long-term planning of energy systems is to select the best alternative among the different renewable energy systems. Gupta et al. (2010) used Mixed Integer Linear Programming (MILP) technique to optimize cost for a hybrid energy generation system. Ashok (2007) presented quasi-Newton method for optimum sizing of hybrid energy system hardware. Cai et al. (2009) discussed the community-scale renewable energy systems planning as an important problem consisting of justifying the allocation patterns of energy resources and services, formulation of local policies regarding energy consumption, economic development and energy structure, and analysis of interactions among economic cost, system reliability and energy-supply security. Some authors have solved this complex problem by applying mixed integer-linear programming (MILP), interval linear programming (ILP) and chance constrained programming to obtain solutions that can provide desired energy resource/service allocation and capacity-expansion plans with a minimized system cost, maximized system reliability and maximized energy security.

With the aim of optimizing the mix of the renewable energy system maximizing its contribution to the peak load, while minimizing the combined intermittence, at a minimum cost, Moura and Almeida (2010) proposed some multi-objective algorithms. Katsigiannis et al (2010) also proposed a multi-objective algorithm which aims to minimize the energy cost of the system, while the total green house gas emissions of the system during its lifetime are also minimized. Practical economic dispatch problems have non-linear, non-convex type objective function with intense equality and inequality constraints. The conventional optimization methods are not able to solve such problems due to local optimum solution convergence. Mahor et al. (2009) presented an application of particle swarm optimization (PSO) to solve this problem and concluded that its performance was better than conventional optimization techniques. Brini et al. (2009) presented a Multi Objective Evolutionary Algorithm (MOEA) for the economic environmental dispatching of a hybrid power system including wind and solar thermal energies that simultaneously minimize the fuel costs and the emission of polluting gases. Bernal-Agustin et al (2009) applied the well known MOEA to the multi-objective design of isolated hybrid systems where the objectives to minimize-are the total cost throughout the useful life of the installation and the pollutant emissions. Bilal Ould et al. (2010) proposed a Pareto-based multi-objective genetic algorithm (MOGA) for sizing a hybrid solar-wind battery system with the aim of minimizing the annualized cost and minimizing the probability of loss of power supply.

Zhou et al. (2010) presented a review of the current state of the art in the simulation, optimization and control technologies for the stand-alone hybrid solar-wind energy systems with battery storage, which concludes that there is a large variety of techniques for accurately predicting their output and reliably integrating them with other renewable or conventional power generation sources. Senjyu et al. (2007) have applied genetic algorithm (GA) for the optimal configuration power system on islands installing a renewable energy power production plant consisting of diesel generators, wind turbine generators, photovoltaic systems and batteries. Koutroulis et al. (2006) also used GA for the optimal sizing of a hybrid system.

1.5 INFERENCES FROM LITERATURE REVIEW

The following points have been inferred from the literature reviewed and discussed above:

i) Renewable energy systems for supplying rural energy demands has emerged out as a prominent area in view of the depleting conventional energy resources and increasing energy demands. The research advancements in this area led to the exposure of the technical limitations, utilization constraints and economic infeasibility of renewable energy resources. Integrated Renewable Energy Systems (IRES) has found to be a good option that can cope up with these limitations. Various integrated systems are found in the literature with the emphasis on supplying electrical demands.

ii) Different combinations of resources as integrated renewable energy system have been reported in the literature. These combinations include solar, wind, hydro and biomass energy resources. In context of Indian rural energy scenario, the three most widely available energy resources are solar, wind and biomass energy resources. This combination of resources has found to be the least explored combination in literature when IRES has been discussed.

iii) The solar and wind energy resources are considered to be the most complex resources as far as their mathematical modeling is concerned. Various mathematical models have been found in the literature, which are, in general, based on either deterministic approach or probabilistic approach. The deterministic approach, being the most common approach, works on considering the average value of the quantity in a given time segment. The limitation with this approach is that this approach is not applicable for time-ahead prediction problems. The probabilistic approach, another mathematical approach found in literature, is based on the representation of the data in a particular probability density function and thereby estimating the probability of the state in which the data lies. Besides, techniques based statistical and non-statistical approaches are also found which, basically, are used for the development of time series models. Nowadays, the development of time series model for solar and wind energy resources has substantial scope in these types of systems.

iv) To develop a time series model, it is important to have a series of data of insolation and wind speed. The continuous data recording, in Indian context particularly for rural areas, is a tedious task. The time series model based on classical regression techniques is highly dependent of data series. The limited availability of solar and wind energy resources' data restrict the scope of classical statistical regression techniques and presents a good opportunity for the application of non-statistical techniques in a area.

v) The application of artificial intelligence, particularly artificial neural network, is still new to the renewable energy system domain. The non-statistical techniques based on artificial neural network are emerging as the good techniques for solar and wind energy modeling to overcome the data availability constraints. Exploration of neural networks for the development of time series models may be considered for further study.

vi) Most of the work reported in the planning of IRES was focused on the sizing of resources. As far as planning of integrated system is concerned, besides sizing, the operational strategy play an important role in analyzing the economics of the system. This left a substantial scope for the development of time-ahead operational strategy with the application of time series modeling of solar and wind energy resources.

vii) As far as optimization techniques are concerned, various optimization techniques were reported in the literature. On the basis of their searching mechanisms, the techniques are categorized as classical, that follow point by point search algorithm and evolutionary techniques that follow population based search algorithms. Classical techniques have limitations of search area and initial value definition. In the similar manner, evolutionary based algorithms have limitations of excess time and complexity. These limitations led to the emergence of hybrid techniques. Different hybrid techniques have been discussed in the literature. The application of these techniques was limited to sizing problems. This opened up a good amount of scope for hybrid techniques for the optimal planning of integrated renewable energy systems.

It can be inferred from the points listed above that integrated renewable energy systems has potential scope of research for supplying rural energy demands. To work on integrated renewable energy systems, it is required to develop the mathematical model of the resources. Time series modeling represent renewable energy resources, particularly solar and wind energy resources, very closely to the real resource data series. Artificial neural network overcomes the constraint of limited data availability. Besides, hybrid optimization techniques are suitable for optimal planning of an integrated renewable energy system.

1.6 OBJECTIVES

In view of the proposed steps stated for the planning of an optimal integrated energy system, the objectives considered in this study are:

(i) To identify an un-energized area with non-feasibility of grid and with sufficient renewable energy resources in order to develop an integrated renewable energy system.

(ii) In order to develop an integrated renewable energy system for the identified area, it is necessary to study the details about the area, available resources and energy demand of the area. Hence, the estimation of the resources available on the site and the load potential of that site is considered as another objective.

(iii) To develop a mathematical model for planning of Integrated Renewable Energy System combining different resources. Keeping in view of the merits of artificial neural network, a time series model of solar and wind energy resources is proposed to develop for the estimation of solar and wind energy resources.

(iv) To develop an optimum operational strategy for the available resources such that the operational cost is minimum in order to supply the demands.

(v) To work out the optimum sizes of the resources considering the optimum operational as well as capital cost. In addition to the operational cost, the capital cost is also proposed to minimize by formulating an overall cost objective function and using evolutionary programming.

1.7 ORGANIZATION OF THE THESIS

The present thesis has been organized into six chapters and the work included in each chapter has been presented in the following sequence:

Chapter-1 gives an overview of energy scenario, introduction of integrated renewable energy systems, the objectives of the study and finally, outlines the organization of presented thesis. It presents a comprehensive literature review of the work done in the area of integrated renewable energy systems, different modeling techniques of renewable energy resources with an emphasis on time series modeling, the optimization techniques used in this area and finally, a summary is presented that includes the inferences from literature.

Chapter-2 discusses criteria for the selection of study area and the demography of selected site. The potential of resources as well as the demand of the site has also been presented in this chapter.

Chapter-3 presents a methodology for the prediction of different resources in a day-ahead scenario.

Chapter-4 consists of the mathematical formulations for identification of the optimum daily operational strategy.

Chapter-5 presents the determination of optimal sizing configuration for the different resources considering the obtained optimal operational strategy.

Chapter-6 concludes the work contained in the main body of the thesis and presents the suggestions for future work.

CHAPTER-2

SITE DESCRIPTION

2.1 GENERAL

In rural and remote areas, the renewable energy resources like solar, wind, hydro and biomass are available in sufficient quantity to satisfy their local demands. In India, there is ample potential of renewable energy resources. The quantum of expenditure involved for laying down an electrical network in hilly regions and the sparsely distributed population in these regions put forward the challenge of setting up a localized network in that region. The viability of this network is an area of study for those regions.

India is a country with large geographic variations. The states and union territories have wide variations in their geography, climate and population density. Most of the states are connected with central electrical utility. Instead of providing electrical supply through national utility to remote and far-flung areas, setting up a localized generation plant presents a good option for such areas. This does not mean that setting up of localized generation plant provides the best solution for all such remote sites. A site study has to be done for reaching out to any conclusion. Various factors need to be considered before going for establishment of such plant. In other words, a proper site has to be selected. The criteria for site selection are discussed in the next section of this chapter.

2.2 CRITERIA FOR SELECTION OF SITE

The criteria considered for the selection of site are as follows:

i) Availability of renewable energy resources

To develop a renewable energy based system, the availability of renewable energy resources in appropriate quantity and in continuous manner is the prime requirement. Although solar and wind energy resources are the omnipresent resources, their intermittent nature limits their usability. Therefore, the foremost requirement for such type of systems is that the resources should be available and extractable up to a minimum optimum level.

ii) Unavailability of conventional energy resources

Despite having many disadvantages, availability of conventional energy resources discourages the use of renewable energy resources. The main advantages of conventional energy resources are their continuous nature and lesser capital investment. Therefore, the unavailability of conventional energy resources is essential for the dissemination of renewable energy resources.

iii) Electrical grid connectivity

The development of renewable based system is economically not viable where the electrical grid connectivity is possible. Although laying off grid in such hilly terrains is in itself a tedious and uneconomical task, it offers the advantages of continuous and clean power supply. Therefore, the non-accessibility of electricity is essential for the development of economical and utilizable renewable energy system.

iv) Load Availability

In general, the population density in remote and far flung areas is very low. It would also be unviable if the load is not sufficient.

v) Distance between load and resource center

The greater the distance between the load and resource center, the more the expenditure on transmission of power. This increase in expenditure can make the system either economically unviable or incapable to satisfy the entire demand.

2.3 STUDY AREA

Considering the criteria of electrical grid non-connectivity, it would be appropriate to consider a remote site. In general, it is difficult and non-economical to lay down an electrical network at mountainous and hilly terrain. Besides, the availability of renewable energy resources and non-availability of conventional energy resources also supports the selection of a site in the state of Himachal Pradesh. Himachal Pradesh (HP) is a state in Northern India. The area of the state is 21,495 sq mi (55,670 km^2) and is bordered by Jammu and Kashmir on the north, Punjab on the west and south-west, Haryana and Uttarakhand on the south-east and by the Tibet Autonomous Region on the east. The map of HP is shown in Fig 2.1.

Himachal Pradesh is divided into 12 districts namely, Kangra, Hamirpur, Mandi, Bilaspur, Una, Chamba, Lahaul and Spiti, Sirmaur, Kinnaur, Kullu, Solan and Shimla. The state capital is Shimla which was formerly British India's summer capital under the name Simla (Maps of India, 2014a).

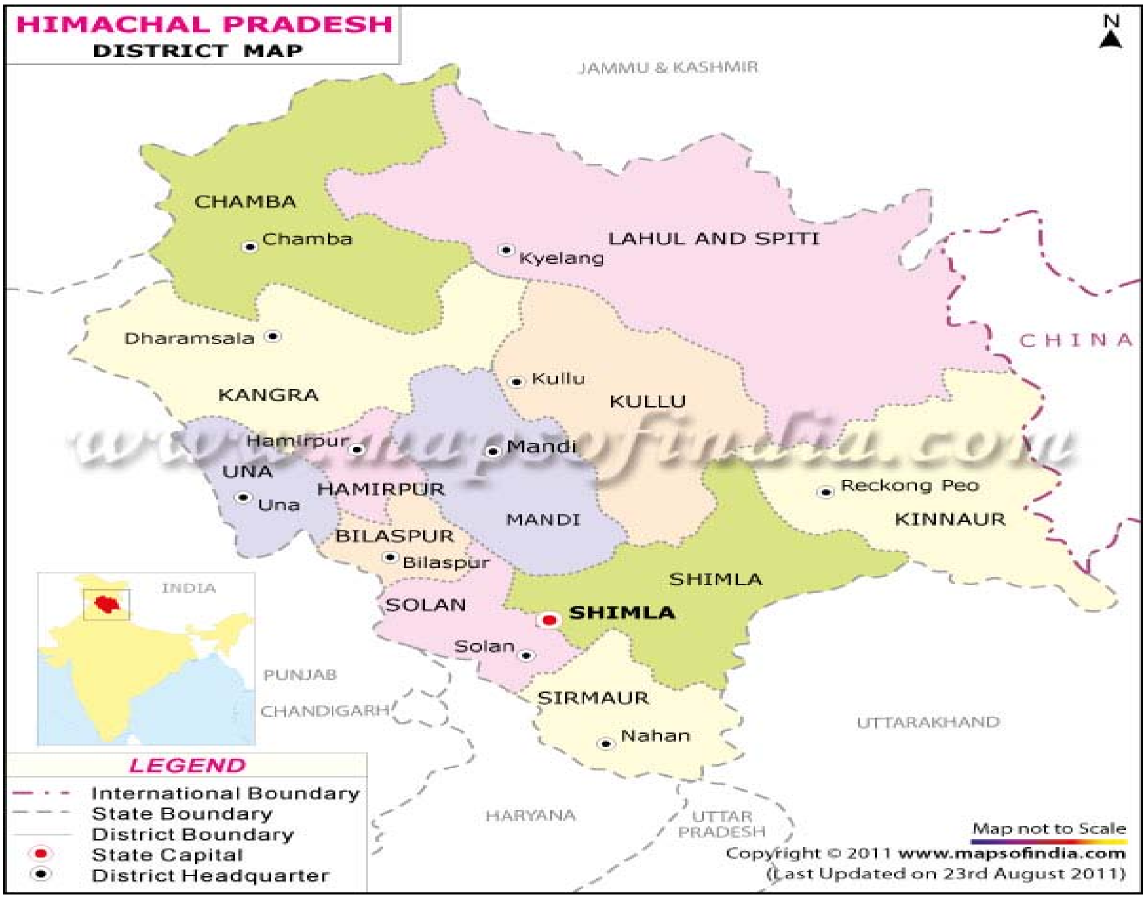


Fig. 2.1: Map of Himachal Pradesh (Maps of India, 2014b)

2.3.1 Electrification in Himachal Pradesh

Because of mountainous terrain, the electricity is not accessible to the entire state. Government of India (GoI) is running several schemes for providing electricity to the remotest of the corner of the country. One such scheme is Rajiv Gandhi Gramin Vidhutikaran Yogna (RGGVY). As per RGGVY, the district-wise electrification status is given in Table 2.1(RGGVY, 2014).

Table 2.1: District-wise village electrification status of Himachal Pradesh

S. No.	District	Total number of villages	Number of Un-electrified / De-electrified villages
1.	Bilaspur	123	0
2.	Chamba	15	14
3.	Hamirpur	131	0
4.	Kangra	670	0
5.	Kinnaur	57	28
6.	Kullu	13	0
7.	Lahul & Spiti	44	22
8.	Mandi	872	12
9.	Shimla	127	1
10.	Sirmaur	46	1
11.	Solan	456	0
12.	Una	6	0

As per the data mentioned in the Table 2.1, Kinnaur has got the maximum number of villages that are yet to be electrified.

2.3.2 Kinnaur District

Kinnaur is one of twelve administrative districts in the state of Himachal Pradesh, India. The district is divided into three administrative areas – Pooh, Kalpa, and Nichar – and has five *Tehsils* (Counties) as shown in Fig.2.2. The administrative headquarter of Kinnaur district is at Reckong Peo. Kinnaur surrounded by the Tibet to the east, in the northeast corner of Himachal Pradesh, about 235 kms from Shimla is a tremendously beautiful district having the three high mountains ranges i.e. Zanskar, Greater Himalayas and Dhauladhar. The old Hindustan-Tibet road passes through the Kinnaur valley.

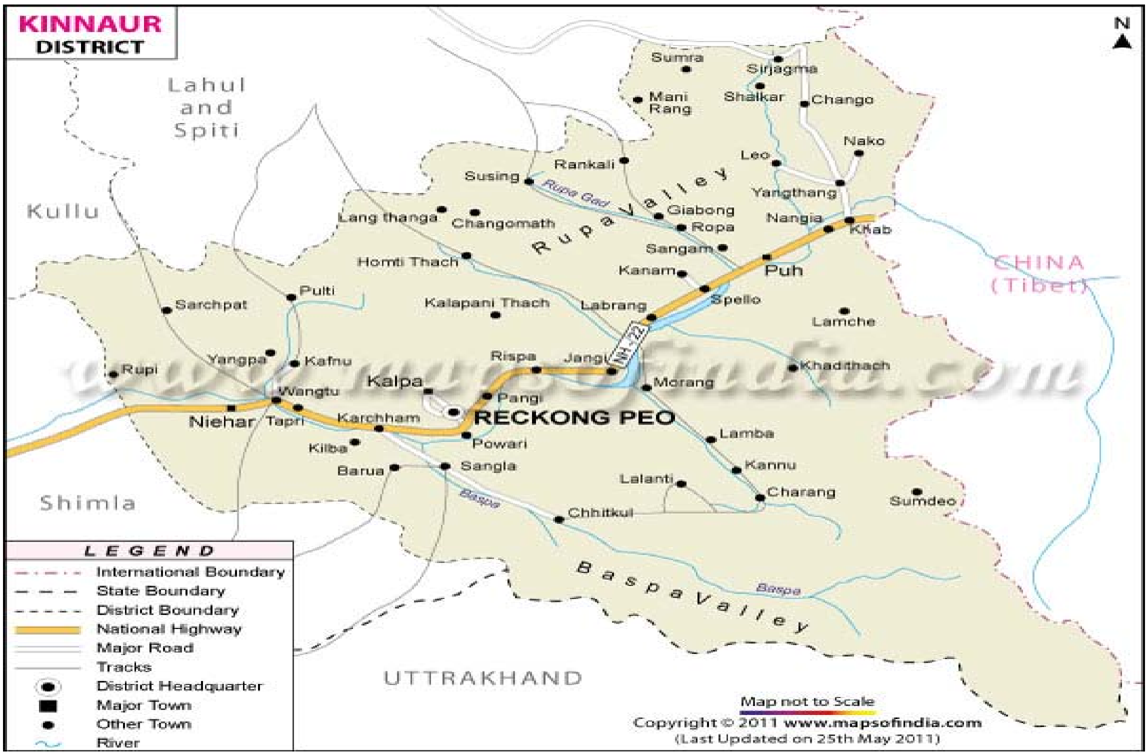


Fig. 2.2: Map of Kinnaur District (Maps of India, 2014c)

According to the 2011 census Kinnaur district has a population of 84,298, roughly equal to the nation of Andorra. This gives it a ranking of 620th in India (out of a total of 640). The district has a population density of 13 inhabitants per square kilometer (34 /sq mi). Its population growth rate over the decade 2001-2011 was 7.61%. Kinnaur has a sex ratio of 818 females for every 1000 males, and a literacy rate of 80.77%.

A remote rural site of Kinnaur district has been selected for the present study on the basis of the criteria discussed. The general information of the site has been given in Table 2.2 (Census of India, 2011a).

Table 2.2: General Information of the selected site (Census of India, 2011a)

Village	Tapri
Sub-District	Nichar (T)
District	Kinnaur
State	Himachal Pradesh
Country	India
Latitude	31.45^{o} N
Longitude	78.05^{o} E
Area of village (Hectares)	459
Number of Households	258

The population of the village is 800 persons with 444 males and 356 females. The average normal household size is 5.0. The bovine population of the area is 825. Among facilities, the area has 02 primary schools, 01 primary health center and 01 post office. The nearest town is at a distance of 84 kms (Census of India, 2011b).

2.4 ASSESSMENT OF DEMAND

It is important to recognize the energy consumption pattern of the rural areas to estimate the load in a rural area. There is a random variation in the rural energy demands which puts up the challenge for this demand estimation. Energy consumption of rural areas can be quantized either through primary data or through secondary data. Though it is a tedious task for rural areas, primary data collected for specific objectives is considered best for any study. Before conducting any survey, it is important to work out the different factors that are to be taken into consideration as energy consumption depends upon several spatial, seasonal, socio-economic and techno-economic factors. While estimating the energy requirements of a rural area, the important factors are – the population of the area, the climate of the area, number of households, number of commercial buildings, the income level, day to day activities and occupation of the people of the area. The variation of these activities with time is also important as some of these activities vary on daily basis and some on seasonal basis.

Secondary data can be obtained through various non-government organizations. These non-government organizations collect, compile and analyze the data and further prepare reports with various objectives. In general, the problem with this data is that this data is erroneous, biased and obsolete as in most cases this data is collected by persons with no prior knowledge of the objective and proper training. This lacuna in secondary data emphasizes the importance of primary data.

A primary survey has been conducted with the objective of working out the rural energy demand. In general, the energy requirements for *Tapri* village may be categorized as energy requirements for domestic purposes, energy requirement for business and energy requirement for leisure or societal development. This domestic energy requirement is confined to cooking and lighting. The main business of natives is agriculture so energy requirement for business implies the energy required for agriculture. Energy requirement for societal development comprises of electricity requirement for common areas like community centers, schools, banks and other commercial buildings. On this basis, the entire energy demand has been classified as mechanical load, thermal load and electrical load.

2.4.1 Mechanical Load

The main occupation of the people of the area is agriculture. The major crop grown in that region is of apple. The different agricultural activities include – tilling, sowing, irrigation, etc. The energy requirements for the activities like tilling, sowing is provided with human and animal power. But, it is difficult to carry out irrigation in such a manner. Hence, the main mechanical energy requirement is for water pumping for irrigation purposes. To estimate the energy requirements for the crop, it is necessary to calculate the water requirements. The total irrigated area at the site is 41 hectares. The water requirements growth stage-wise is given in Table 2.3. Based on the Table 2.3, a minimum of 1ML/ha/season and a maximum of 5ML/ha/season of water for irrigation is required depending upon the rainfall during that season. Taking a conservative approach and assuming a minimum rainfall, the higher side of irrigation demand is considered in the study.

Table 2.3: Growth stage-wise water requirements for the site (APAL Australia, 2012)

Growth Stage	Month	Water requirements (ML/ha/month)
Budburst and Flowering	September	0.3
	October	0.5
Rapid Shoot Growth	November	1.2
	December	1.5
Beginning of fruit fill	January	1.5
	February	1.2
	March	1.1
Harvest	April	0.5
	May	0.3
Leaf fall	June	0.1
	July	0.1
	August	0.2
Total Water Requirement (ML/ha/season)		8.5
Total Irrigation Demand (ML/ha/season)		1-5

With the irrigated area of 41 ha, the total irrigation demand of water is 205ML/season. To pump this water from a lift of 100ft, a pump of 12.80 kW is required. This mechanical load may be considered as deferrable load.

2.4.2 Thermal Load

The primary thermal load is cooking. As far as thermal load is concerned, it is assumed that the cooking demand is constant throughout considered time segment and is the energy required to cook meal two times a day. A representative meal is consisting of 0.3kg of rice, 0.2kg of pulses and 0.3kg of potatoes. The energy required to cook this meal is 1.43MJ (Kumar et al.,1996). This meal is considered for a family size of 4-5persons. Total cooking energy requirement is estimated by considering the representative meal twice a day for every household in the village.

2.4.3 Electrical Load

The area has currently very low electrical demand. In this study the electrical load is estimated considering the future requirements of the area as well. Electrical load is sub-categorized as domestic and commercial load. Domestic electrical load includes the electrical energy requirements of households. Commercial electrical load include the energy requirements of commercial joints/buildings that are, market places, post office, banks and schools. The site comprises of two primary schools, two primary dispensaries, one post office and one co-operative bank, in addition to households. Hence, the total scope of electrical energy consumption is summarized in Table 2.4.

Table 2.4: Main premises of electrical energy consumption

Premises	**Numbers**
Households	258
Primary Schools	02
Ayurvedic Dispensary	01
Primary Health Care Center	01
Post Office	01
Telegraph Office	01
Commercial Bank	01
Co-operative Bank	01

The electrical energy requirement for these premises is either for lighting and/or for space heating. Table 2.5 and 2.6 show the current electrical energy requirements. The availability of electricity would open up the scope for the development of some small scale industries which can help in the enhancement of economic level of the natives. Considering small scale industries like mini dairy plant, mini cold storage and mini milk processing plant, the annual electrical energy requirement has been presented in Table 2.7.

Table 2.5: Domestic electrical energy requirements

Premises	Energy Consumption per household (kWh/yr)	Annual Energy Consumption (kWh/yr)
Fan Load	61	31476
Space heating	305	45750
Lighting	146	75336
Total		152562

Table 2.6: Commercial electrical energy requirements

Premises	Operational Hours	Annual Energy Consumption (kWh/yr)
Primary Schools	06	73
Ayurvedic Dispensary	08	122
Primary Health Care Center	08	122
Post Office	08	98
Telegraph Office	08	98
Commercial Bank	08	98
Co-operative Bank	08	98
Total		707

Table 2.7: Expected electrical energy requirements

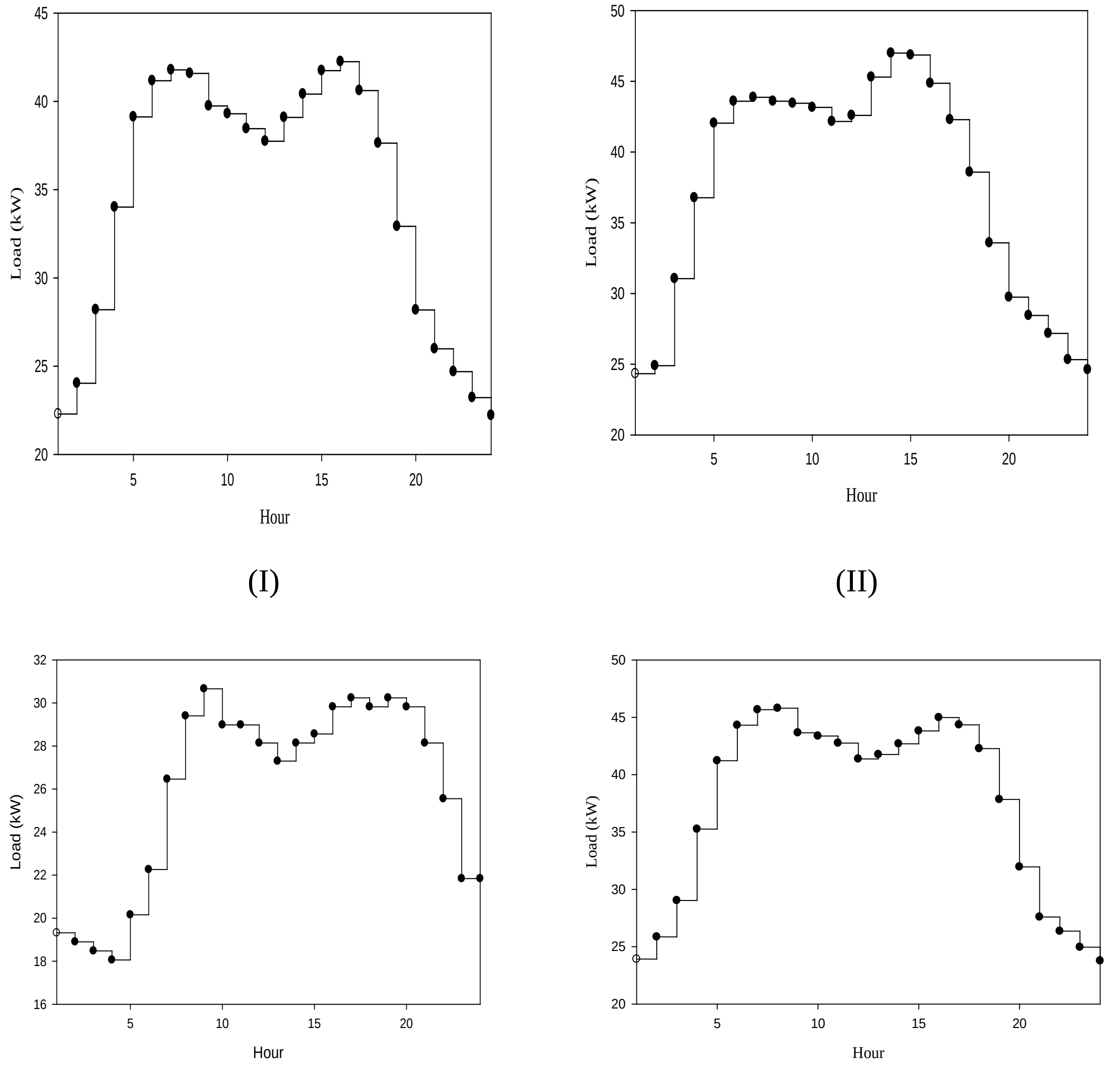
Unit	Duration of use	Energy per day (kWh/day)	Annual power (kWh/year)
Mini Dairy plant	8	29.84	10892
Milk Processing plant	6	13.20	3828
Mini Cold Storage	10	37.30	2275
Total			16995

Besides total energy requirement, it is also important to look into the hourly pattern of the energy requirement as electrical load is hourly as well as seasonally variable load. In order to work out the hourly load pattern, the entire time period is divided into small time segments, that is, the whole year is divided into four seasons and a typical day is selected to represent the season. The year has been divided as Dec-Feb as season – I, Mar – May as season – II, Jun – Aug as season – III and Sep – Nov as season – IV.

The load profile gives a complete idea of the hourly variation of load. It is important to analyze the hourly variation of load as this helps in proper allocation of resources at a particular time segment for a particular load. Basically, load profile is required for the optimization of scheduling problem.

To obtain the hourly load profile, the daily activities of the people of the area has been studied and their hourly energy requirements are recorded. The source of data is mainly through village heads. It is assumed that variations during the day are same as any other day of the season.

The hourly load profile is as shown in Fig. 2.3.



(I) (II)

(III) (IV)

Fig. 2.3: Seasonal load profile

2.5 ASSESSMENT OF RESOURCES

The selection of the type of renewable energy that can be installed at a particular location requires a previous analysis of the availability of resource. The results of such an analysis will provide necessary information about the generation capacity that needs to be installed for a given demand, as well as distribution over time of that resource. Among different renewable energy resources, the most commonly used resources are solar, wind and biomass.

2.5.1 Solar Energy

Solar energy is the most abundant, inexhaustible and clean of all renewable energy resources till date. In any solar energy conversion system, knowledge of global solar radiation is extremely important for the optimum design and forecasting of the system's performance. The sun's radiation is subject to many absorbing, diffusing, and reflecting effects within the earth's atmosphere which is about 10 km average thick and, therefore, it is necessary to know the power density, i. e., watts per meter per minute on the earth's outer atmosphere and at right angles to the incident radiation. The density defined in this manner is referred to as the solar constant. The best value of the solar constant available at present is 1360W/m^2 (Parida et al., 2011). To estimate the potential, the solar radiation data on the respective coordinates of the site has been taken from NASA online database (NASA USA, 2012) and presented in Table 2.8.

Table 2.8: Solar radiation values for the site (NASA USA, 2012)

Month	**Average monthly solar radiation (kWh/m^2/d)**	**Yearly (kWh/m^2)**
Jan	2.85	88.35
Feb	3.37	94.36
Mar	4.28	132.68
Apr	5.10	153.00
May	6.03	186.93
Jun	6.10	183.00
Jul	5.65	175.15
Aug	5.30	164.30
Sep	5.19	155.70
Oct	4.88	151.28
Nov	3.86	115.80
Dec	2.95	91.45
Annual		1689.95

The figures of solar radiations at the site are quite optimistic and encouraging for the setting up of solar based applications at the site. For the specified site, the average yearly insolation was estimated to be 1689.95kWh/m^2.

2.5.2 Wind Energy

The wind turbine captures the wind’s kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power production capacity. The kinetic energy in air of mass “m” moving with speed V is given by the following in SI units:

$$KE = 1/2.m.V^2 \tag{2.1}$$

The power in moving air is the flow rate of kinetic energy per second. Therefore:

$$P = 1/2.(mfr).V^2 \tag{2.2}$$

where, P is mechanical power in the moving air, ρ is air density, kg/m^3, A is area swept by the rotor blades, m^2, V is velocity of the air, m/s and mfr is the mass flow rate. The volumetric flow rate is A·V, the mass flow rate of the air in kilograms per second is ρ·A·V, and the power is given by the following equation,

$$P = 1/2.C_P(\rho.A.V).V^2 = 1/2.C_P.\rho.A.V^3 \tag{2.3}$$

To estimate the wind energy potential, it is mandatory to measure the wind speed at different time instants as well as heights for the site. The average wind speed at the mast height of 10m has been presented in Table 2.9 (NASA USA, 2012).

As far as the specified site is concerned, the average wind speed at 10m height is in the range of 3.9 – 5.6 m/s. The highest of 5.6 m/s has been recorded in the month of December.

Table 2.9: Wind speed values for the site

Month	Wind speed at 10m mast height (m/s)
Jan	5.4
Feb	5.4
Mar	5.2
Apr	5.0
May	5.3
Jun	5.1
Jul	4.1
Aug	3.9
Sep	4.3
Oct	5.2
Nov	5.5
Dec	5.6

The wind speed values mentioned in Table 2.9 shows that there is sufficient scope of wind energy utilization.

2.5.3 Biomass

Biogas energy (or bioenergy) is energy derived from organic matter. Biomass can be considered as all materials that have the property of being decomposed by biological effects, that is, by the action of bacteria. Biomass can be decomposed by methanegenic bacteria to produce biogas, in a process depending on factors such as temperature, pH, carbon/nitrogen ratio, and the quality of each. Usable and accessible organic matter includes animal residue, agricultural residue, water hyacinth (Eichornia crassipes), industrial residue, urban garbage, and marine algae. There exists a potential biomass use for animal feces produced in cattle farming, which is easily mixable with water. To estimate the daily volume of biogas production, it is important to have the knowledge of the animal waste produced and the population of animals. The waste production in kg per day and the corresponding volume of gas in m^3 per day has been presented in Table 2.10. The volume of biogas produced depends upon the collection efficiency of the waste.

Table 2.10: Amount of waste per animal and corresponding gas production

Manure Animal	**Numbers**	**Production (kg/Day)**	**Total dung per day (kg)**	**Gas Produced (m^3/kg)**	**Total gas produced per day with collection efficiency (80%) (m^3/day)**
Bovines	367	10.00	3670	0.036	105
Equines	239	6.50	1553.5	0.036	45
Oviparous	165	0.77	127.05	0.062	6
Suidae	54	2.25	121.5	0.078	8
Total					164

It is to be noted that the site presents an ample potential of solar, wind and biomass energy resources in order to meet out the demands of the people of the area. The available resources have to be utilized in an integrated manner. For planning of an integrated renewable energy system, it is important to predict the near future data of resources. A day-ahead prediction of solar and wind resources have been presented in the next chapter.

CHAPTER-3

DAY – AHEAD PREDICTION OF RESOURCES

3.1 GENERAL

The data of solar and wind energy resources discussed in Chapter 2 are found quite encouraging in terms of the development of IRES to meet out the estimated demand. The data presented in the previous chapter was based on the current scenario. When it comes to planning, it is important to have the data in a future-ahead scenario. This future – ahead may be quantized into different scenarios as- hour-ahead, day-ahead, etc. For such type of situations, where the demand is not varying hourly in great proportion, it is appropriate to consider day-ahead scenario. Day-ahead scenario implies prediction of the availability of resources, particularly solar and wind due to their variable nature, on hourly basis for the next day. There are different approaches for the development of mathematical models of solar and wind energy resources. One such approach is time series modeling (Chatfield, 1996). Time series modeling has been widely used in day-ahead modeling of solar and wind energy resources (Mellit et al., 2004; 2005; 2009). Forecasting time series is an important component of the planning of a system comprising of solar and wind energy resources. Although modeling the time series is considered as statistical problem, various non-statistical techniques (Aguiar and Pereira, 1992; Hokoi et al., 1990; Knight et al., 1991; Maafi and Adane, 1989) are also available to forecast the time series. The limitations with statistical techniques are:

i) The data requirement for predicting the next series value is rigorous.

ii) Besides, the data requirement, the data handling in statistical approaches is very complicated.

iii) In addition, in case of statistical techniques, the problem has to be defined comprehensively for accurate prediction.

Besides, these methods get restricted with noisy or non-linear components which are common in real-world situations. To overcome such limitations, ANN based techniques are, nowadays, widely used for forecasting solar and wind time series. With the help of ANN based time series modeling, certain limitations of data availability and complexity in correlation developments has been overcome. The basic idea is to train a neural network with past data and then use this network to predict the future values. This chapter presents an artificial neural network based approach for day-ahead prediction of renewable energy resources mainly wind speed and solar radiations. RBF network has been used to simulate a day-ahead forecasting model for solar and wind energy resources. The hourly values of a day ahead has been predicted for solar and wind energy resources in order to evaluate the power available from solar and wind energy resources during that time segment of the day. The neural network toolbox of MATLAB has been utilized to develop the model.

Unlike solar and wind energy resources, the variability of biomass is negligible particularly on hour basis. This clearly indicates the inapplicability of day-ahead scenario and also limits the development of time series in the case of biomass.Therefore, a daily average has been obtained and the power output is kept constant for the day in case of biomass.

3.2 RADIAL BASIS FUNCTION NETWORK

Neural network is defined as a massively parallel distributed processor made up of simple processing units, which has a natural propensity for storing experimental knowledge and making it available for use. It resembles the brain in two respects:

i) Knowledge is acquired by the network from its environment through a learning process.

ii) Interneuron connection strengths, known as synaptic weights, are used to store the acquired knowledge.

Radial Basis Function (RBF) network uses radial basis function as the base of hidden units that constitute the hidden layer. There are certain advantages of RBF network over other networks like in RBF network, solution of clustering problem can be performed independently, and also, output in scarcely trained input is not random in RBF. Basically, it involves three layers with entirely different roles. The input layer is made up of source nodes that connect the network to the environment. The second layer, the hidden layer, applies a non-linear transformation from the input space to the hidden space. The output layer is linear, supplying the response of the network to the activation pattern applied to the input layer as shown in Fig.3.1.

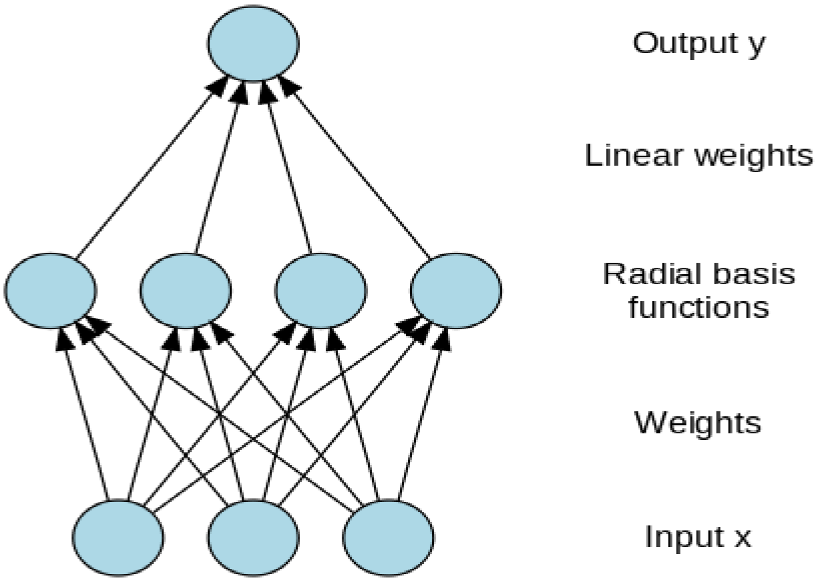


Fig. 3.1: Architecture of Radial Basis Function Network

Due to their non-linear approximation properties, even complex mappings can be modeled through RBF networks. Each of the hidden units implements a radial basis function.

The interconnection between input and hidden layer form hypothetical connection and between hidden and output layer form weighted connections. The output, $\varphi : \Re^n \to \Re$, of the network is thus,

$$\varphi(x) = \sum_{i=1}^{n} a_i \rho(\|x - c_i\| \tag{3.1}$$

where n is the number of neurons in the hidden layer, c_i is the center vector for neuron i, and a_i are the linear weights of the output neuron. In the basic form all the inputs are connected to each hidden neuron. The norm is typically taken to be the Euclidean distance and the basis function is taken to be the Gaussian.

$$\rho(\|x - c_i\|) = \exp[-\beta\|x - c_i\|^2] \tag{3.2}$$

The Gaussian basis functions are local in the sense that

$$\lim_{\|x\|\to\infty} \rho(\|x - c_i\|) = 0 \tag{3.3}$$

i.e. changing parameters of one neuron has only a small effect for input values that are far away from the center of that neuron (Chen et al., 2009). As far as training is concerned, RBF networks are mainly trained with supervised training algorithms. In supervised training algorithms, a set of data samples called training sets are provided for which the corresponding network outputs are known.

Radial basis networks consist of two layers: a hidden radial basis layer of S1 neurons, and an output linear layer of S^2 neurons as shown in Fig. 3.2.

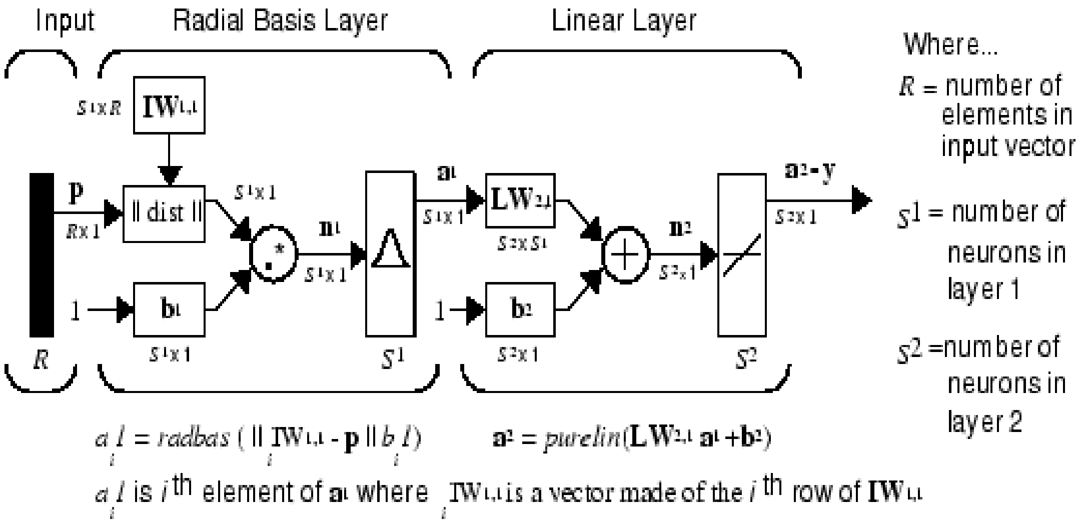


Fig. 3.2: Radial Basis Function Network Architecture

The || dist || box in this figure accepts the input vector p and the input weight matrix $IW^{1,1}$, and produces a vector having S^1 elements. The elements are the distances between the input vector and vectors $iIW^{1,1}$ formed from the rows of the input weight matrix. For RBF networks, the training set is used for the training to estimate the parameters for all possible combination of hidden neurons and spread constant.

3.3 FORECASTING OF RENEWABLE BASED ENERGY RESOURCES

The most important requirement for the development of the model of solar and wind energy resource is the hourly data of these resources during previous year. A generalized flow diagram for the development of solar and wind energy model has been presented in Fig. 3.3. The proposed network utilizes solar radiation and wind data as input in order to predict the future data.

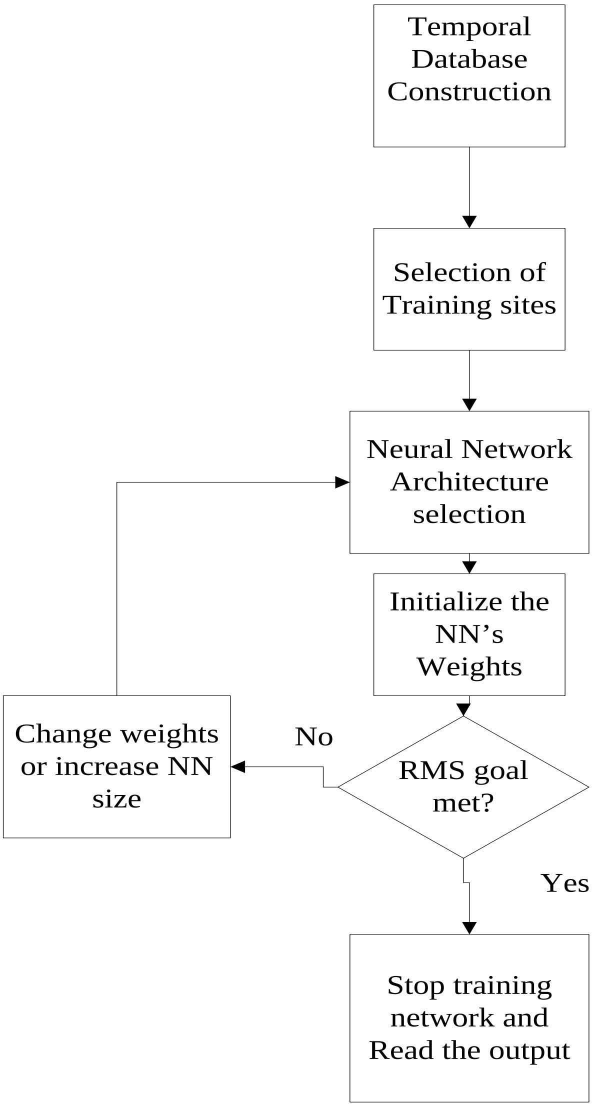


Fig. 3.3: Flow Diagram for NN based model development

As first step to model development, temporal database needs to be constructed. For solar and wind model development, the hourly data of insolation and wind speed are to be arranged in a time sequence in a matrix. Considering the minimal seasonal variation, the entire data is divided into four seasons. This data is then processed through the selected neural network architecture for the target values with minimum root mean square error and regression coefficient. The future values are predicted.

In this study, an hourly annual data of solar radiations and wind speed for the site described in previous section has been taken from (NASA, USA, 2012) and has been plotted in Fig. 3.3. The annual data has been divided into four segments on the basis of different seasons. In other words, the total 8760 observations has been divided into four seasonal segment with each season of 2160 observations. The seasons are classified on the basis of minimum variation of solar radiations and wind speeds.

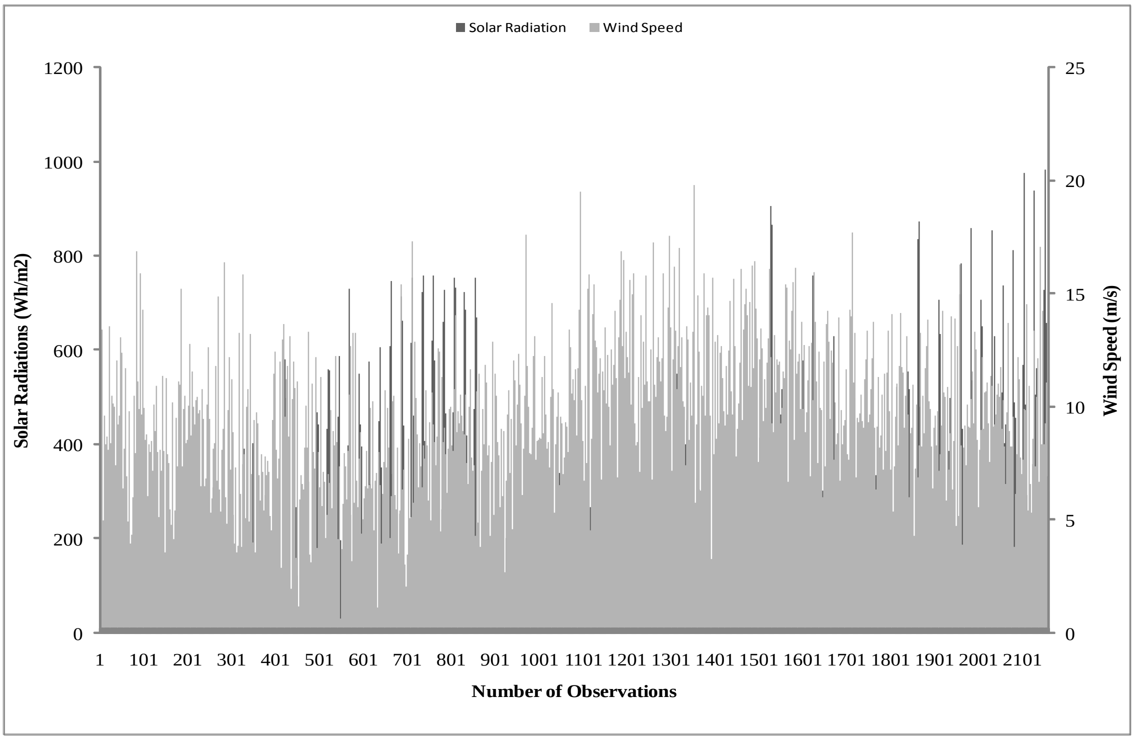


Fig. 3.4 (a): Solar radiation and wind speed during Season I

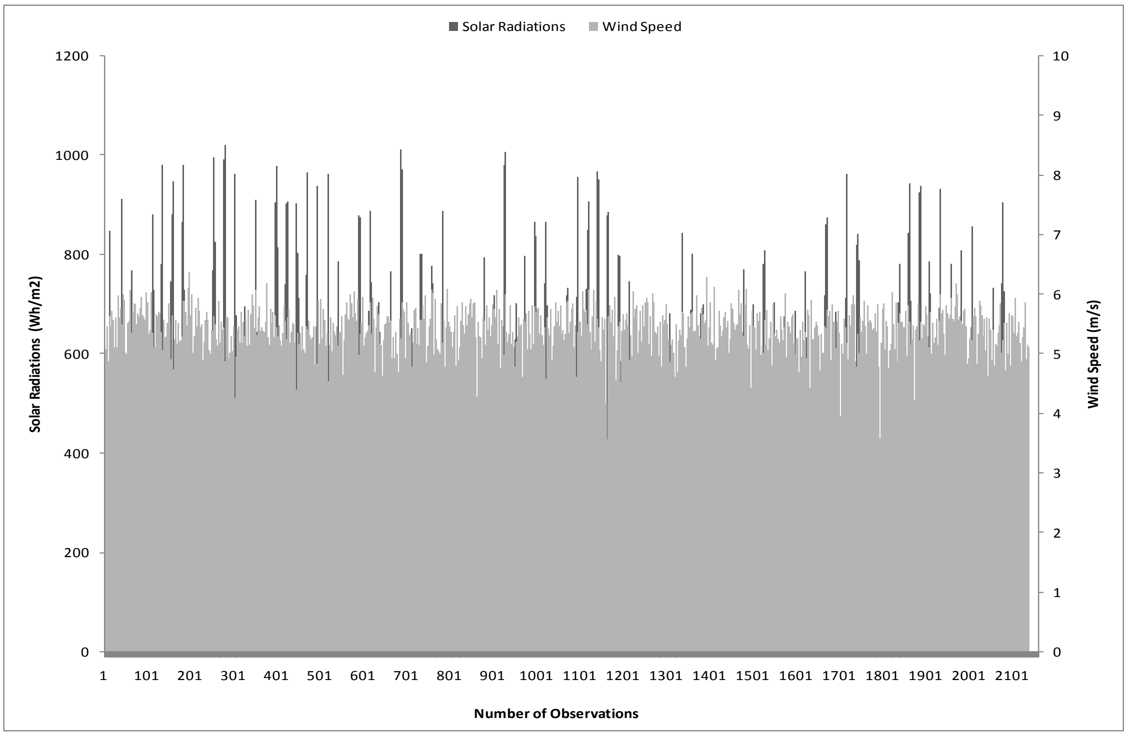


Fig. 3.4 (b): Solar radiation and wind speed during Season II

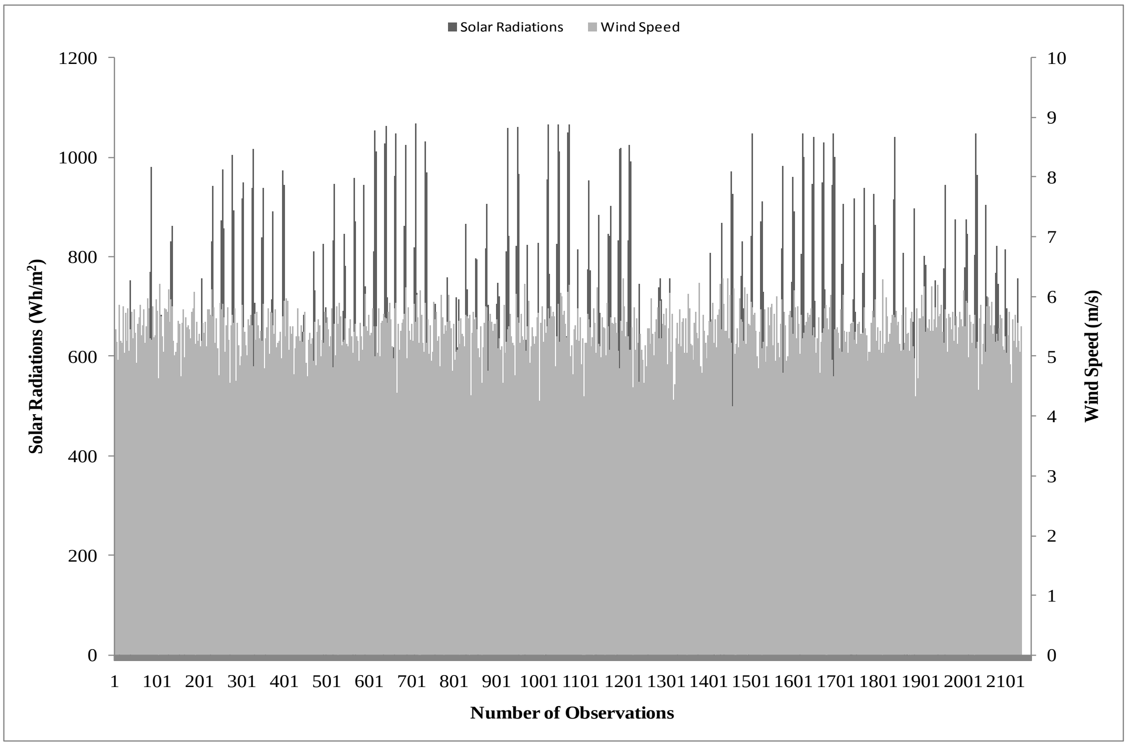


Fig. 3.4 (c): Solar radiation and wind speed during Season III

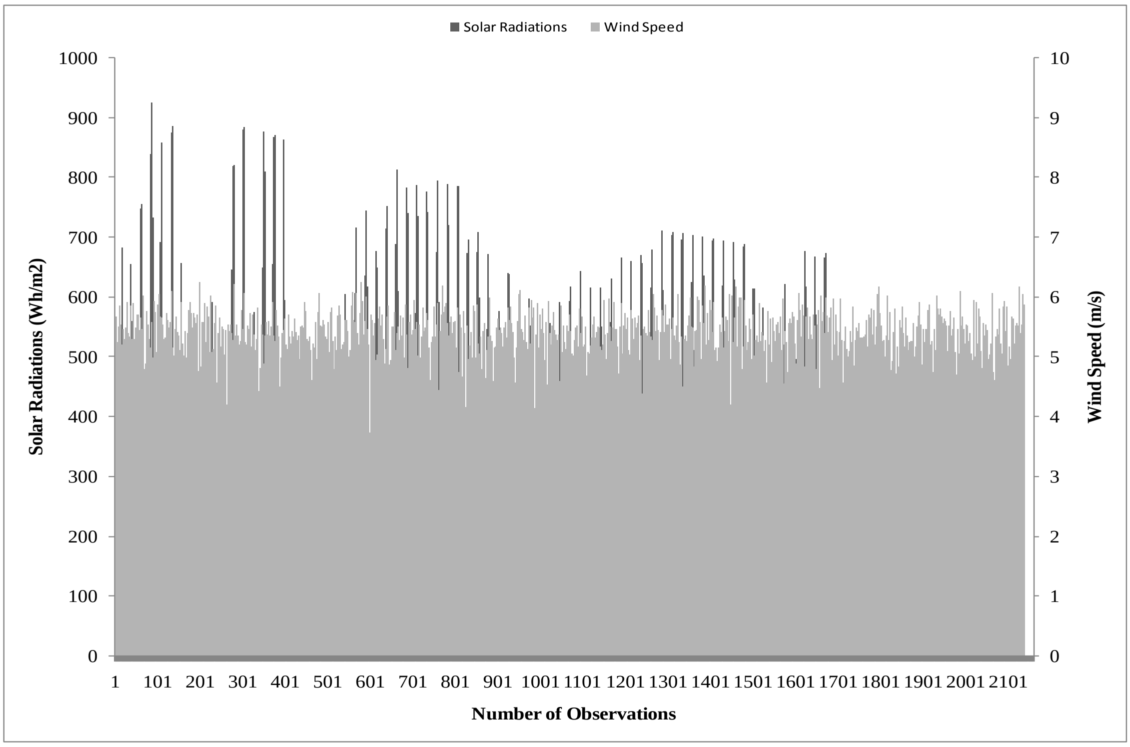


Fig. 3.4 (d): Solar radiation and wind speed during Season IV

To start with, the data set of season I, 2160 points in total, are split into three smaller sets: the training, testing and validation sets. Using ad-hoc approach, which is considered to be the most popular approach, the 70% of the data points are taken for the training of the network and the rest of the data points are equally divided for testing and validation of the network (Maier et al., 2010).

The evaluation set, which is unknown during training phase, is used to check the progress of network. The model used for the prediction set is the one whose parameters minimize the RMS error of the evaluation set. The performance of each forecasting method is measured on the prediction set. With the help of this network, the next 24 values for solar radiations and wind speeds were estimated and thereby, the hourly power potential of solar and wind energy resources were calculated for the study. The model is then simulated for all seasons.

In order to validate the developed model, the regression (R) coefficient for each model has been checked. The R – coefficient measures the correlation between ouputs and the targets. The R-value should be close to unity. The R-value of 1 implies that the target data has been completely converged to the output data.

Besides R-value, the root mean square error (RMSE) between the predicted values and measure values of solar radiations and wind speeds is also a good measure of the acceptability of the developed model. The RMSE is calculated as (Khatib et al., 2011):

$$RMSE = \frac{\sqrt{\sum_{t=1}^{N} (P_{Forecasting} - P_{True})^2}}{N} \tag{3.4}$$

Where, $P_{Forecasting}$ is the forecasting results at each time segment, P_{True} is the historical data at each time segment, t represents the time segment and N represents data sample scale.

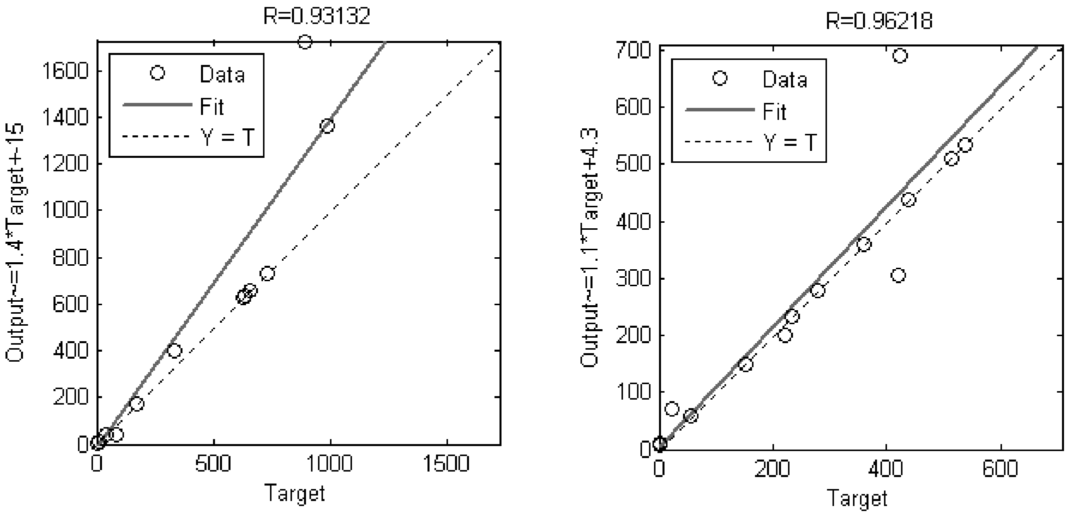
3.4 SOLAR AND WIND MODEL SIMULATION

The model discussed in the previous section has been simulated in the Neural Network Toolbox of MATLAB. The toolbox is widely acceptable and has inherent features of RBF network with supervised training algorithms. The Levenberg-Marquardt (LMS) algorithm has been used as training algorithm (Hacouglu et al., 2008).

The network has been simulated season-wise and the ouput data has been obtained for a day of that season which is considered to be the representative day. A representative day is defined as the day which depicts the features of that season and if multiplied by the number of days of that season, the total resource as well as load can be analysed with minimum error.

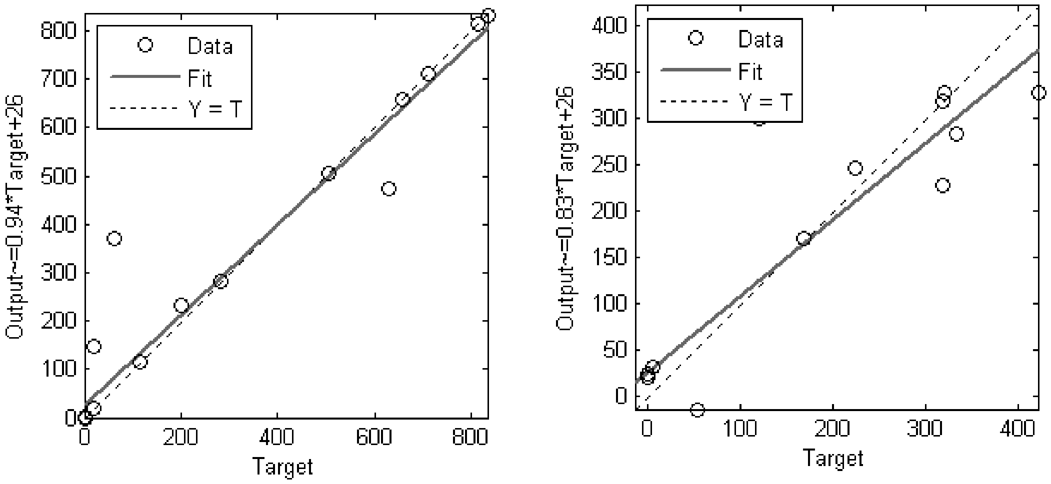
For training the network, the input data has been prepared in the matrix of 90×24 The target data is provided in the matrix of 1×24. The number of neurons in the hidden layer is taken as 20. The model is then trained. The training automatically stops when the generalization stops imporving. The R-values and the RMSE values are then obtained in order to evaluate the performance of the developed model.

In this study, the model is simulated season-wise and resource-wise. The overall regression (R) coefficients for solar radiations and wind speeds, as obtained, are shown in Fig.3.5 and Fig.3.6 respectively. The R-values made the model acceptable for the study. The RMSE for solar radiation and wind speeed are presented in Table 3.1 and Table 3.2 respectively.



Season I

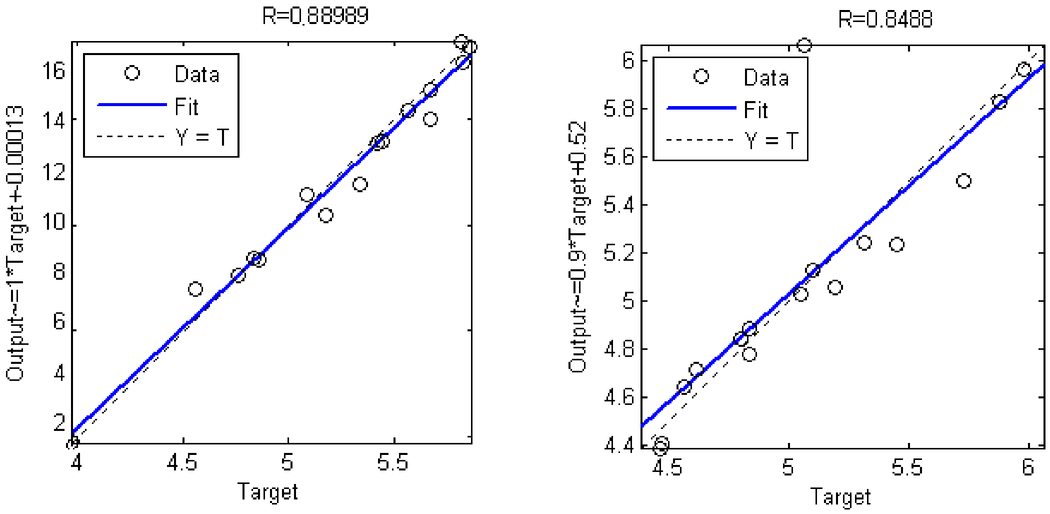
Season II



Season III

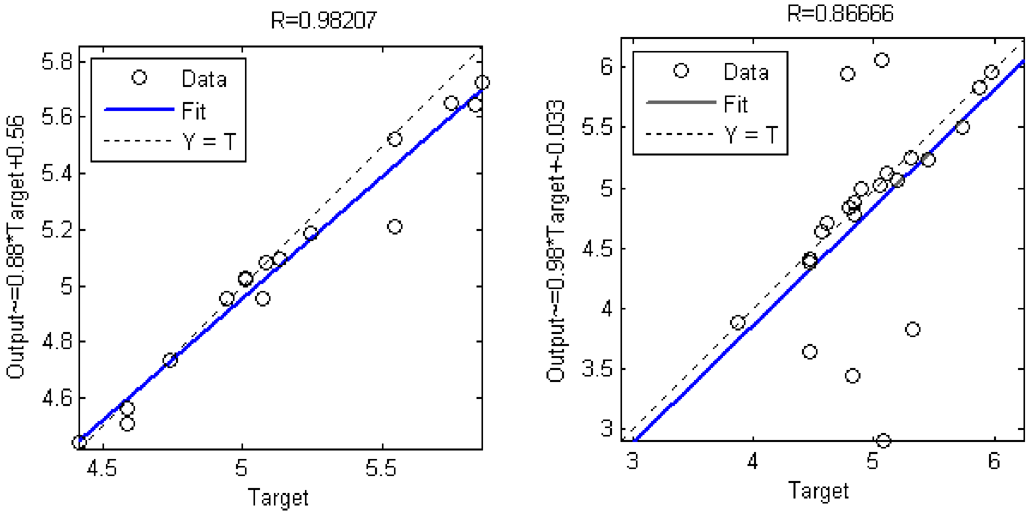
Season IV

Fig. 3.5: R-Coefficient for solar radiations for different seasons



Season I

Season II



Season III

Season IV

Fig. 3.6: R-Coefficient for wind speeds for different seasons

Table 3.1: Season-wise Root Mean Sqaure Error values for solar radiations

Radiation Data	**RMSE (%)**
Season I	1.76
Season II	1.84
Season III	1.96
Season IV	1.65

Table 3.2: Season-wise Root Mean Sqaure Error values for wind speeds

Wind speed	**RMSE (%)**
Season I	1.55
Season II	1.60
Season III	1.93
Season IV	1.72

This considered neural network system has been simulated for all four seasons to forecast the solar radiations and wind speeds. The predicted solar radiations along with the target values for the considered four seasons are shown in Figs.3.7-3.10.

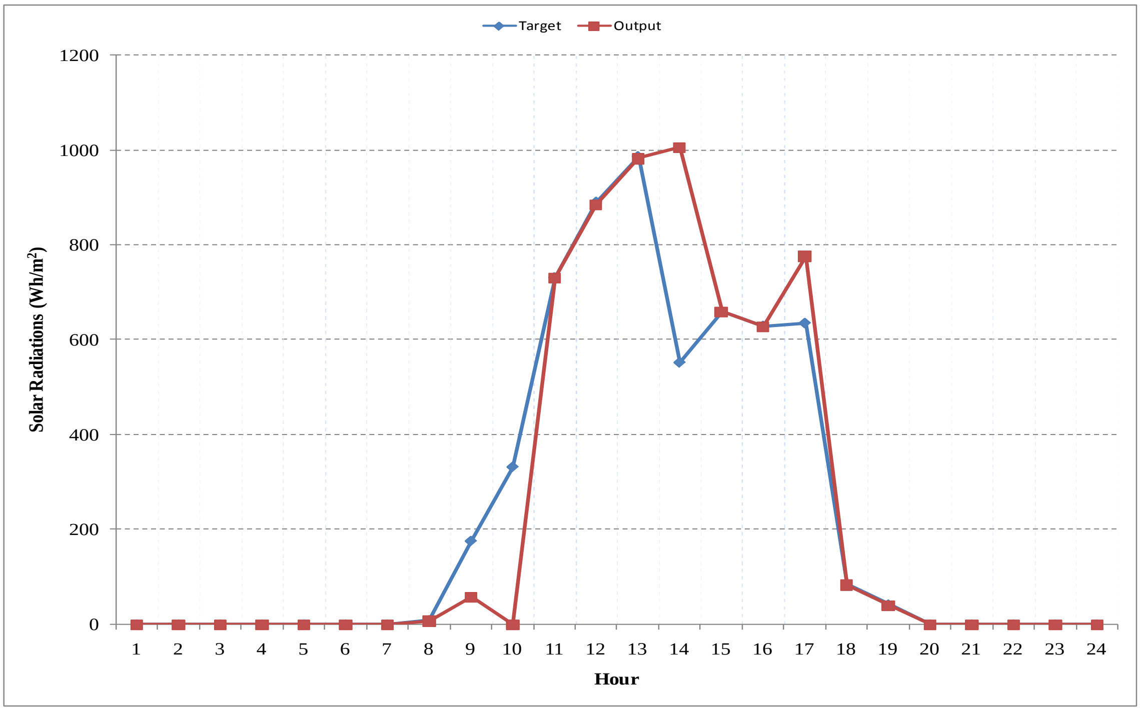


Fig. 3.7: Target and Output insolation for Season I

The graph clearly depicts a normal day with a good availability of solar radiations for nearly 8 hours during this season. The trend comply with the actual conditions.

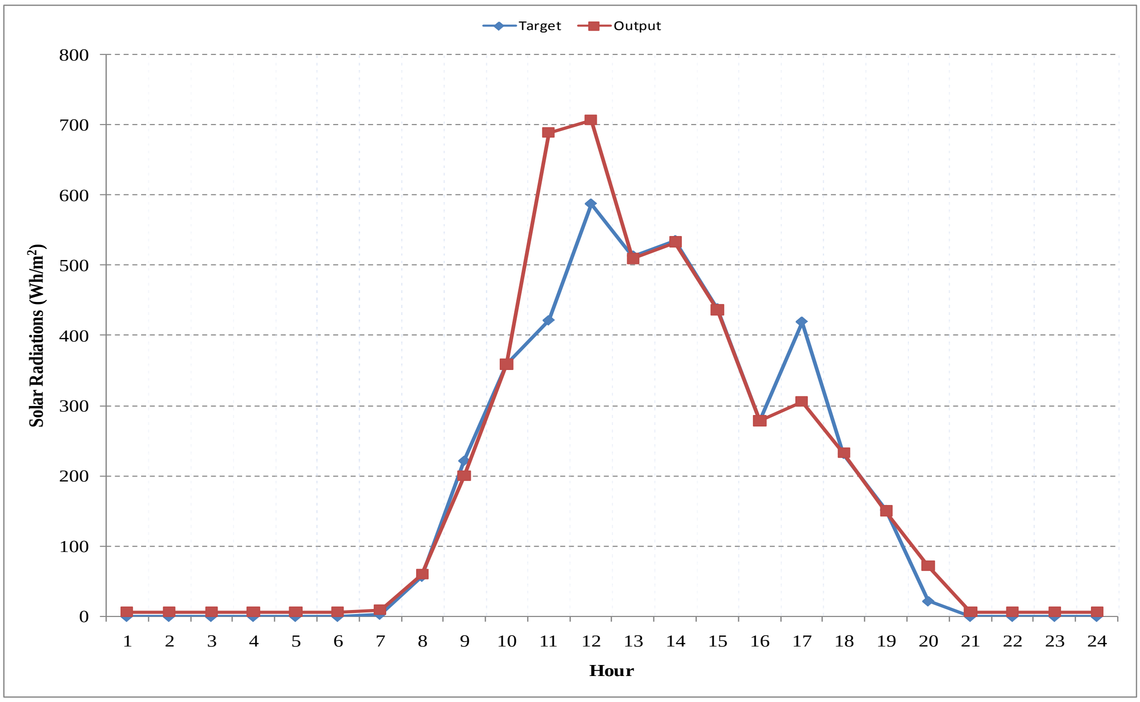


Fig. 3.8: Target and Output insolation for Season II

During season-II, the solar radiations are variable throughout the day. The trend is rising and then decling during the later hours of the day which is in compliance with the real situations.

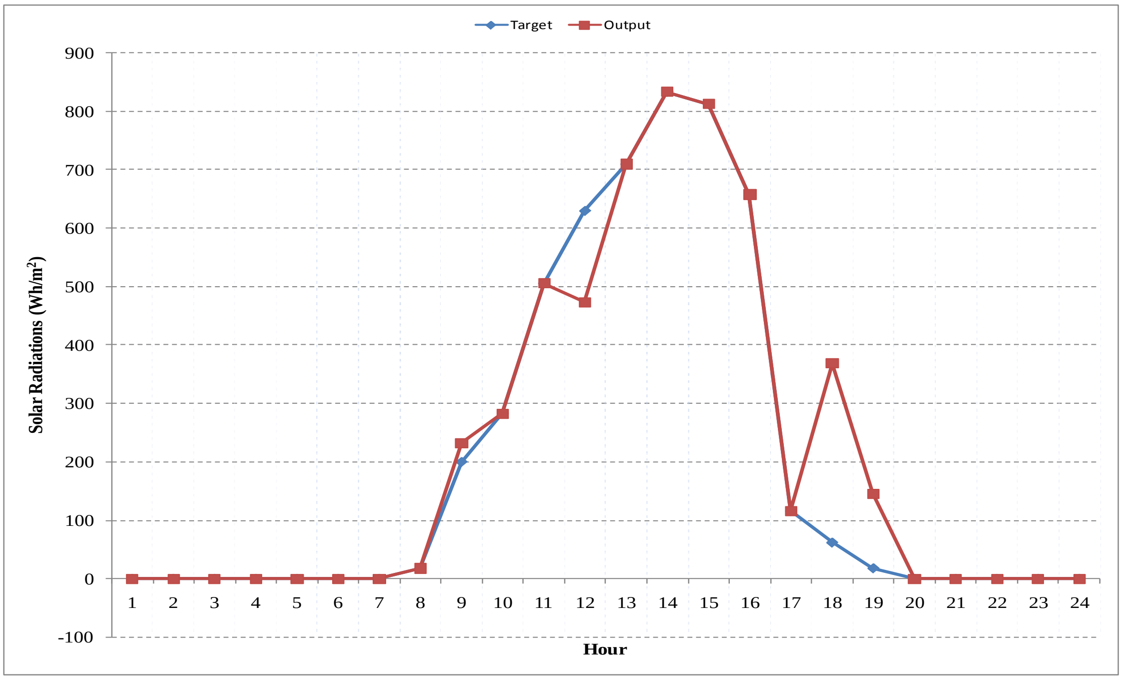


Fig. 3.9: Target and Output insolation for Season III

The trend of solar radiations is found to be in good agreement with the real time situations except a slight hike during the later hours of the day.

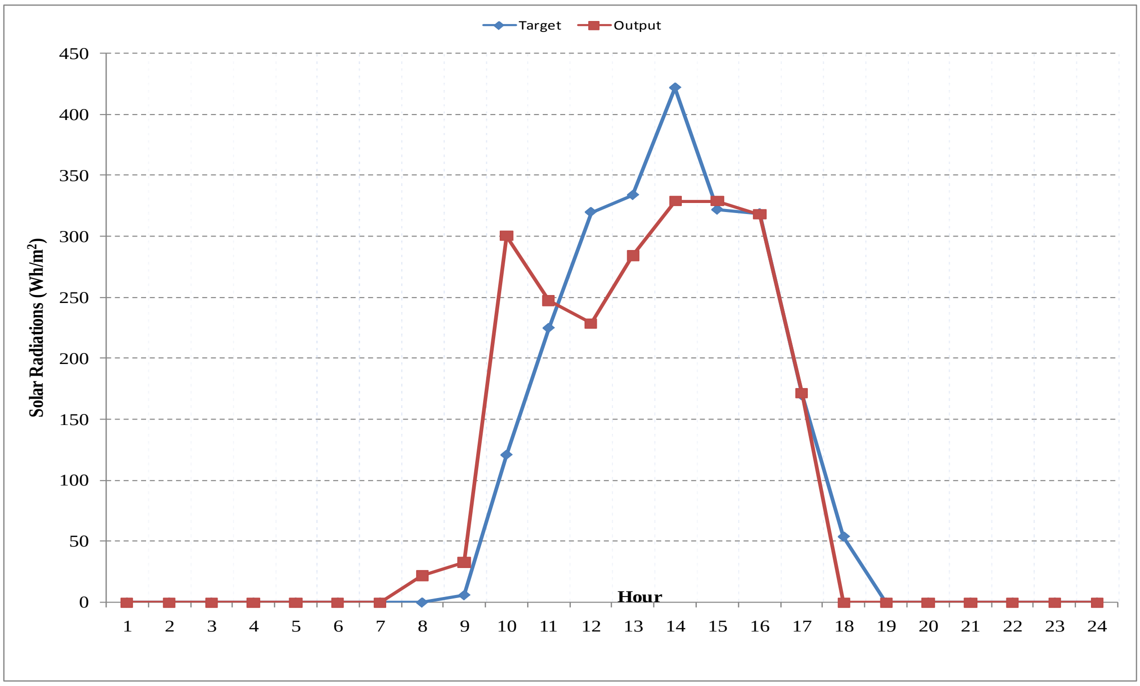


Fig. 3.10: Target and Output insolation for Season IV

The insolation values are quite good for most part of the year. During season-IV, the weather becomes cold and foggy. This reduces the insolation availability during that season. As far as daily solar radiations are concerned, the radiations are available for most part of the day. The season-wise predicted values are presented in Table 3.3.

Table 3.3: Predicted Hourly Solar Insolation in (Wh/m^2) for a representative day

Hour	Season 1	Season 2	Season 3	Season 4
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0

Contd….

Hour	Season 1	Season 2	Season 3	Season 4
7	0	0	0	0
8	7.70	60.08	18	21.94
9	57.07	200.02	232.06	32.90
10	0.00	359.07	283	300.61
11	730.57	689.38	506	247.58
12	885.92	707.39	473.76	228.82
13	982.48	509.82	710	284.26
14	1005.91	533.52	834	329.04
15	659.58	436.64	813	328.95
16	628.76	278.58	658	318.53
17	776.77	305.94	116	171.38
18	83.49	232.55	369.14	0
19	40.47	150.08	145.73	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	0
24	0	0	0	0

The target and output wind speeds for the considered four seasons are shown in Figs. 3.11-3.14.

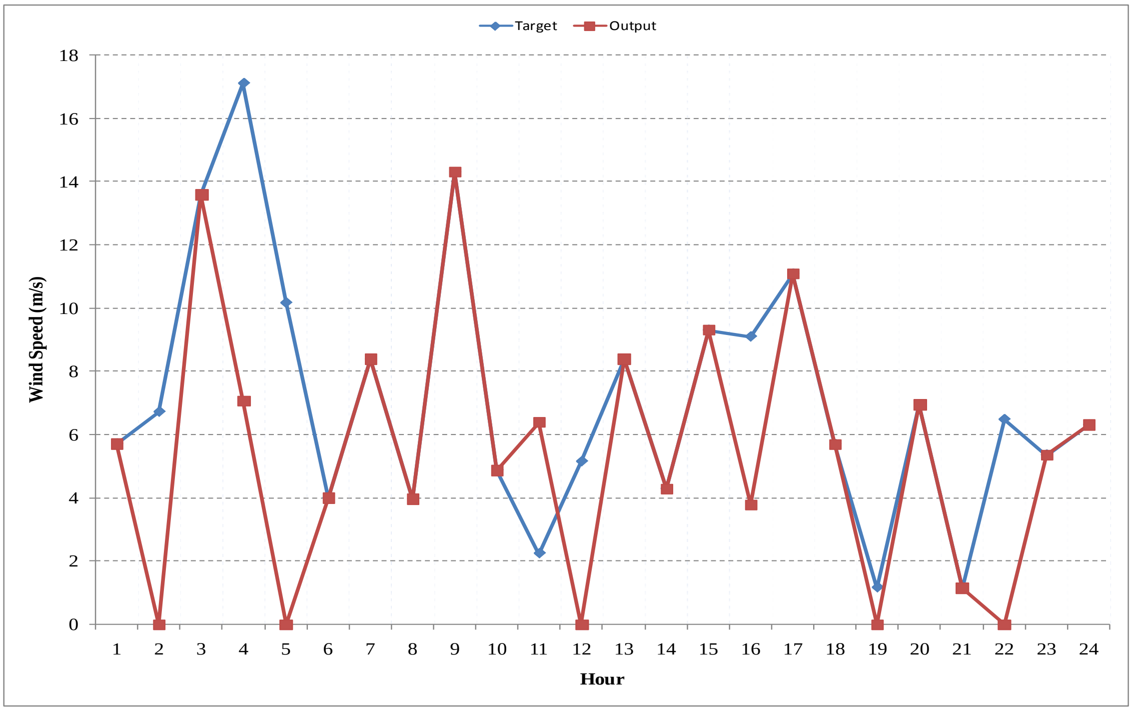


Fig. 3.11: Target and Output wind speeds for Season I

The wind speeds during this season is relatively higher than other three seasons. With the root mean square value of 1.55% and the regression coefficient greater than 0.8, the predicted values very much comply with the real situations.

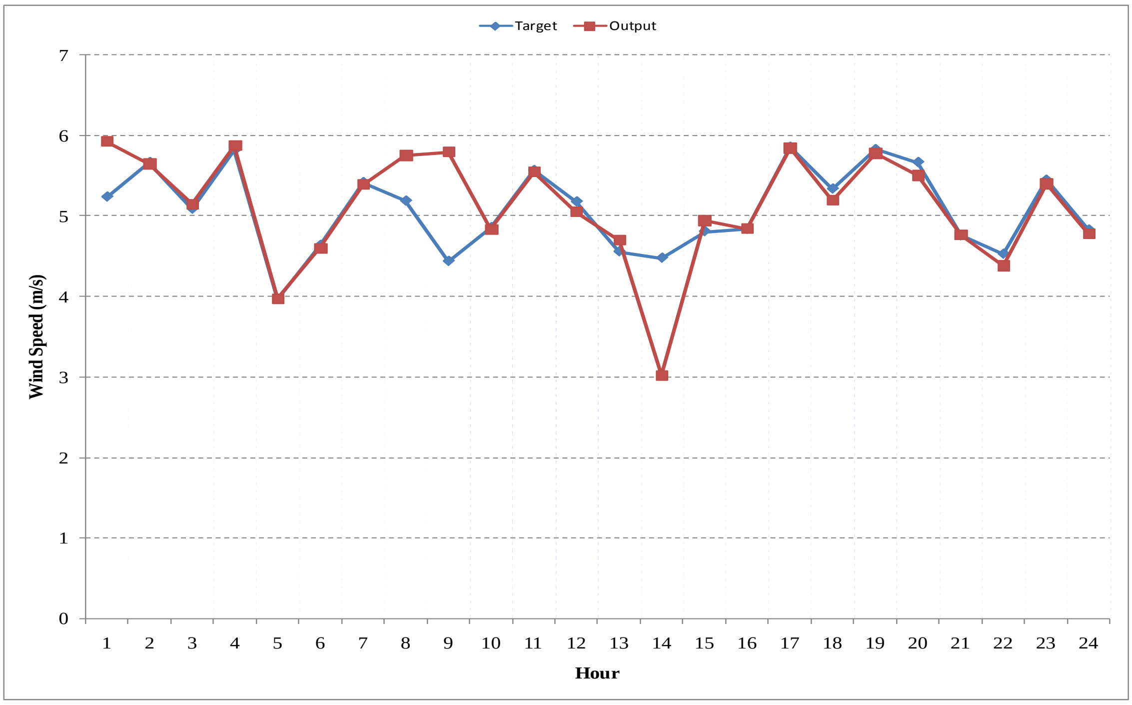


Fig. 3.12: Target and Output wind speeds for Season II

The predicted hourly wind speeds for the representative day of Season II is shown in Fig. 11. In this case, the root mean square value is 1.6% and the value of regression coefficient is 0.84.

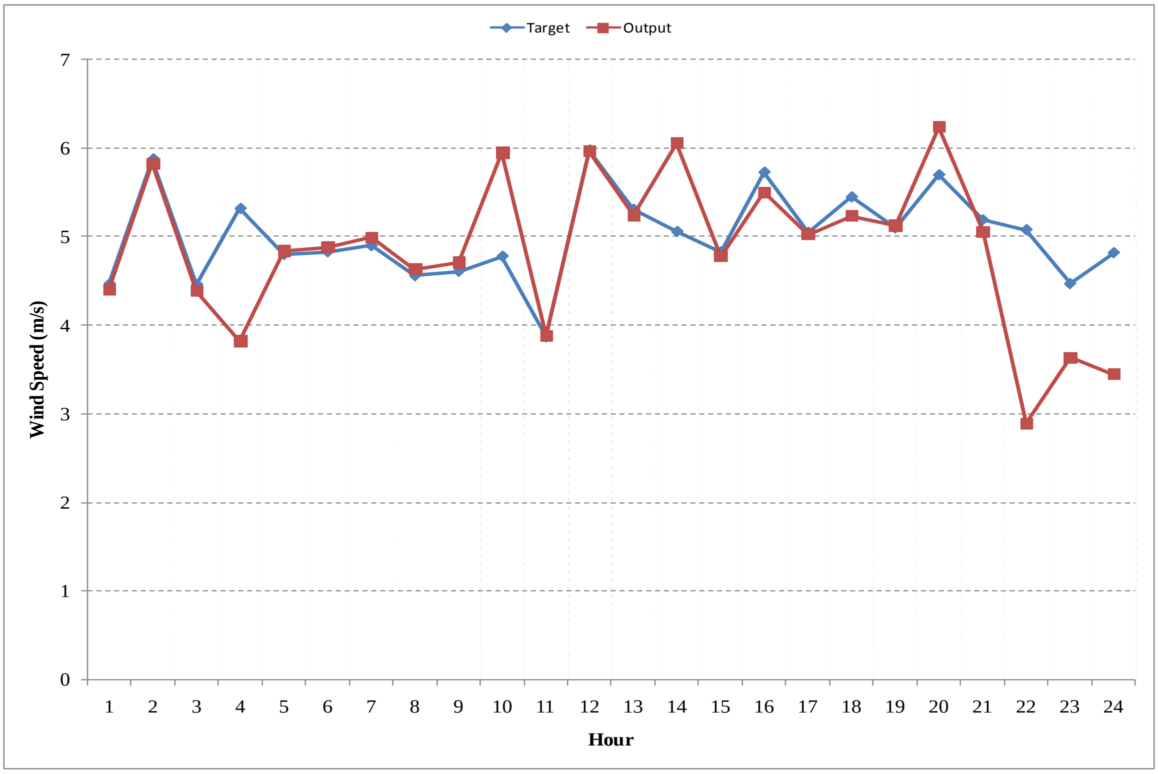


Fig. 3.13: Target and Output wind speeds for Season III

The predicted hourly wind speeds for the representative day of Season II is shown in Fig. 11. In this case, the root mean square value is 1.93% and the value of regression coefficient is 0.98.

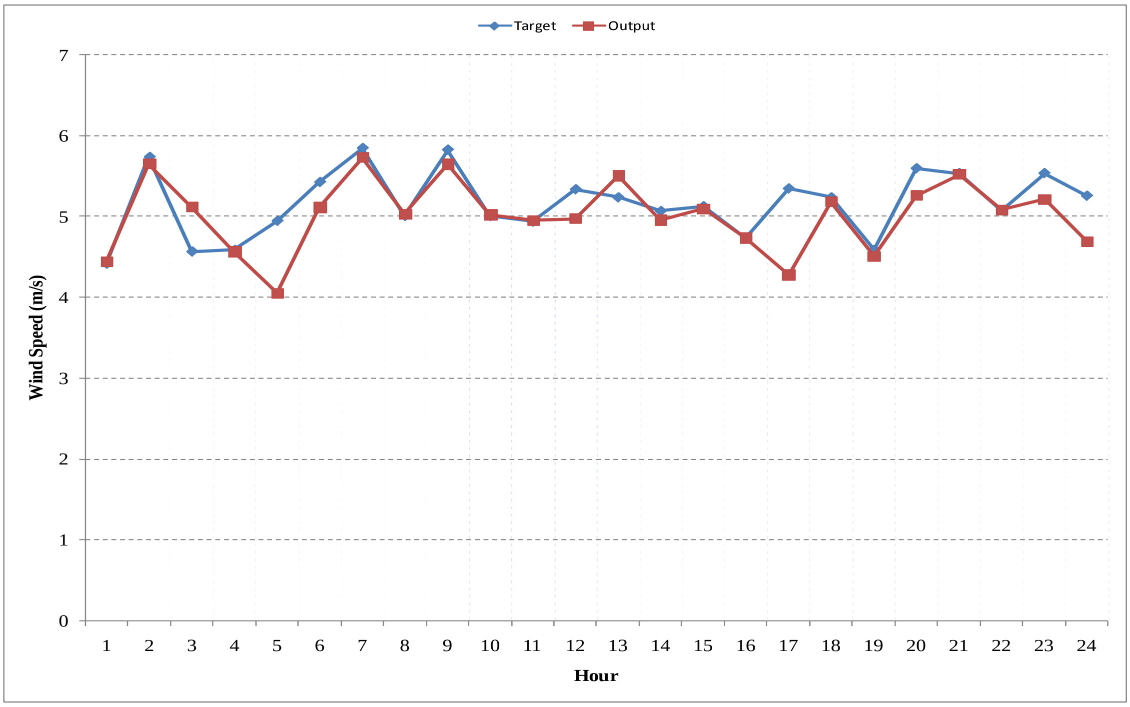


Fig. 3.14: Target and Output wind speeds for Season IV

The predicted hourly wind speeds for the representative day of Season II is shown in Fig. 3.12. In this case, the root mean square value is1.72% and the value of regression coefficient is 0.86. The season-wise predicted values are presented in Table 3.4.

Table 3.4: Predicted Hourly wind speed in (m/s) for a representative day

Hour	Season 1	Season 2	Season 3	Season 4
1	5.71	5.92	4.40	4.44
2	0	5.64	5.83	5.65
3	13.59	5.15	4.39	5.12
4	7.07	5.87	3.82	4.56
5	0	3.98	4.84	4.06
6	4	4.60	4.88	5.11
7	8.39	5.39	4.99	5.73
8	3.97	5.75	4.64	5.03

Contd…..

Hour	Season 1	Season 2	Season 3	Season 4
9	14.3	5.79	4.71	5.64
10	4.87	4.83	5.95	5.02
11	6.39	5.54	3.88	4.95
12	0	5.05	5.97	4.98
13	8.39	4.70	5.24	5.50
14	4.29	3.03	6.06	4.96
15	9.31	4.94	4.78	5.09
16	3.78	4.84	5.50	4.74
17	11.09	5.84	5.03	4.28
18	5.69	5.19	5.23	5.18
19	0	5.77	5.13	4.51
20	6.95	5.50	6.24	5.26
21	1.15	4.77	5.06	5.52
22	0	4.38	2.89	5.08
23	5.36	5.40	3.64	5.21
24	6.31	4.78	3.45	4.69

Although this site is not wind prone, the wind energy potential can be extracted through low speed wind turbines.

3.5 BIOMASS MODELING

To estimate the biogas potential, data for the number of manure animals in the region has been collected. It is difficult to find the hourly data of available biomass which limits the application of the modeling techniques in case of biomass. In addition, the biomass production does not have the similar variability as was the case of solar and wind energy resources. An average value is, therefore, considered for biomass availability.The values presented in Table 3.5, represents the waste collected from different sources, particularly animal waste.The data presented in Table 3.6 is primary data and is taken from the site with the help of locals.

Table 3.5: Biomass collected in (kg) for a typical day

Season 1	**Season 2**	**Season 3**	**Season 4**
55	57	54	56

Table 3.6 presents an ample potential for biomass for biogas production. For the typical day of season I, the biogas production will be 1.98m^3 as the biogas produced per kg of animal dung is 0.036m^3 (Gupta et al., 2011).

It can be understood that time series modeling is essential for the segment-wise estimation of resources especially solar and wind energy resources because of their time-variant nature. Non-statistical based approaches, particularly ANN based approaches, provide a simplicity and accuracy to the modeling process. RBF Network can map even the complex models because of their non-linear approximators properties. The suitability of the developed model for solar and wind energy resources can be judged on the basis of R-values (>0.8) and RMSE values (< 2%). Low rating wind turbines and solar panels will be able to suffice the load requirements of the site. The modeling of biomass is difficult due to the lack of data availability in Indian scenario.

CHAPTER-4

OPTIMAL OPERATIONAL STRATEGY

4.1 GENERAL

In the previous chapters, considering the intermittent nature of solar and wind energy, the day-ahead values of solar radiations and wind speeds have been predicted through non-statistical techniques. The next step to this problem is their utilization. Despite, various technological advancements, the solar and wind energy resources utilization requires wide dissemination due to their variable behavior. It is an area of research worldwide to overcome this drawback. Various alternatives have been suggested and implemented that suffice the variability of solar and wind energy and provide a reliable solution to the problem. Among various solutions, the utilization of different resources in tandem, such that the shortcomings of individual resources can be overcome, has been considered as one of the best solutions. Development of such systems would make the energy available even at the remotest of location and/or at uneven terrains where it is economically unviable to lay down grid connectivity. The work reported in this area clearly emphasizes and encourage the development of such systems.

While designing such systems, the most adequate operational strategy has to be looked upon. The operational strategy significantly affects the system performance and thereby the operating cost. The problem of sharing the load among generators with an exclusive electrical load in a system in the most economic manner has been studied extensively and various control strategies have been developed and applied (Won and Fung, 1993; Berley et al., 1995; 1996; Muselli et al., 1999; Dufo-Lopez and Bernal-

Agustin, 2005; 2007; Kohle, 2012; Seeling-Hochmuth, 1997). The dispatch strategy determines the energy flows from the various sources in such a way as to optimize system performance in terms of operating cost.

Various dispatch strategies has been discussed (Barley and Winn, 1996) for a system comprising PV, wind generators, diesel generators and batteries. The focus of the strategies was on fuel usage and battery life and an analytical approach has been used to obtain the economic dispatch strategy. Similarly, in (Berley and Winn, 1995) dispatch strategies like load following strategy, cycle charging strategy and combined strategy has been discussed for a PV-diesel system. The system has been simulated and optimized in HOGA software.

It can be noted from the literature that different combination of resources as integrated renewable energy system has been reported. These combinations include solar, wind, hydro and biomass energy resources. In context of Indian rural energy scenario, the three most widely available energy resources are solar, wind and biomass energy resources. This combination of resources has found to be the least explored combination in literature when IRES has been discussed. In addition, most of the work reported in the planning of IRES was focused on the sizing of resources. As far as planning of integrated system is concerned, besides sizing, the operational strategy play an important role in analyzing the economics of the system. This left a substantial scope for the development of time-ahead operational strategy with the application of time series modeling of solar and wind energy resources.

In this chapter, an optimization problem has been formulated to identify the optimum daily operational strategy for IRES. IRES comprises of solar, wind and biomass generators to allocate the electrical, thermal and mechanical demands with suitable conversion facilities. The MATLAB codes have been developed to minimize the cost of operation considering component and system constraints.

4.2 POWER OUTPUT FROM RENEWABLE ENERGY BASED CONVERSION FACILITY

As discussed in Chapter 2, the site has the availability of resources like solar, wind and biomass. The day-ahead hourly values of solar and wind energy has been predicted using ANN based technique in Chapter 3. These values are going to be utilized to estimate the hourly power output from the solar and wind energy resources. It is necessary to know the hourly power output and the hourly demand in order to coin out a dispatch strategy for the different resources.

a) Solar based energy conversion facility

Hourly power output from PV system with an area A_{PV} (m^2) on an average day of jth month, when total solar radiation of I_T (kW/m^2) is incident on PV surface, is given by:

$$P_{PV} = I_{Tj}\eta A_{PV} \tag{4.1}$$

where, η is system efficiency.

b) Wind based energy conversion facility

The power output from a wind turbine, WT depends on its rated power P_r, cut-in speed V_{ci}, rated speed V_r and cut-out speed V_{co}. The mathematical function relating the power output from a WT with the wind speed can be written as (Chedid et al., 1998):

$$P_{WTG} = \begin{cases} 0, V < V_{ci} \\ aV^3 - bP_r, V_{ci} < V < V_r \\ P_r, V_r < V < V_{co} \\ 0, V > V_{co} \end{cases} \tag{4.2}$$

where, P_{WT} is a function of wind speed V for calculating power output from a WT. Constants a and b are the functions of Vci and Vr, and can be obtained by the following relations (Chedid et al., 1998):

$a = P_r /(V_r^3 - V_{ci}^3)$ (4.3)

$b = V_{ci}^3/(V_r^3 – V_{ci}^3)$ (4.4)

The forecasted hourly mean wind speed in ms^{-1} has been used in this study.

c) Biomass based energy conversion facility

The power output from biomass depends upon the volume of gas (V_{BT}) consumed in time (t) and is expressed as:

$P_{BT} = V_{BT} \times CV \times t$ (4.5)

Also, for mechanical power from biomass based facility, the mechanical power output from a biomass based conversion facility is given by:

$P_{BM} = \eta \times m \times CV$ (4.6)

Where, m is the mass of fuel (kg/s), η is the thermal efficiency and CV is the calorific value of fuel.

Under the present study, total demand is categorized into three categories – electrical, thermal and mechanical. Electrical demand comprises of electrical energy requirement for lighting, space heating applications and small scale industries. Thermal energy is mainly used for cooking applications. Mechanical energy requirement is mainly considered for water pumping applications.

As far as rural demand is concerned, an estimation of thermal, electrical and mechanical energy requirements has been presented in Chapter 2. The load data has been obtained from primary as well as secondary sources. Electrical demand varies throughout the day. Thermal demand mainly comprises of cooking so vary during the sunshine hours of the day. Mechanical demand comprises mainly of water pumping load and can be met during the lean hours of the day.

4.3 PROBLEM FORMULATION

A complete renewable energy based solution to the rural needs is proposed in this study. To obtain an optimum operational strategy, the objective is to minimize the operating cost. There are three resources and three categories of load considered in this study. With the three available resources –solar, wind and biomass and the three types of load – thermal, electrical and mechanical and the availability of appropriate conversion facility, different combinations are made for demand and supply in order to formulate the problem. It has been tried to fulfill all the three types of demands in a particular time segment at a minimum operating cost of the three resources and also considering the constraint of energy conversion facility. The system considered is shown in Fig. 4.1.

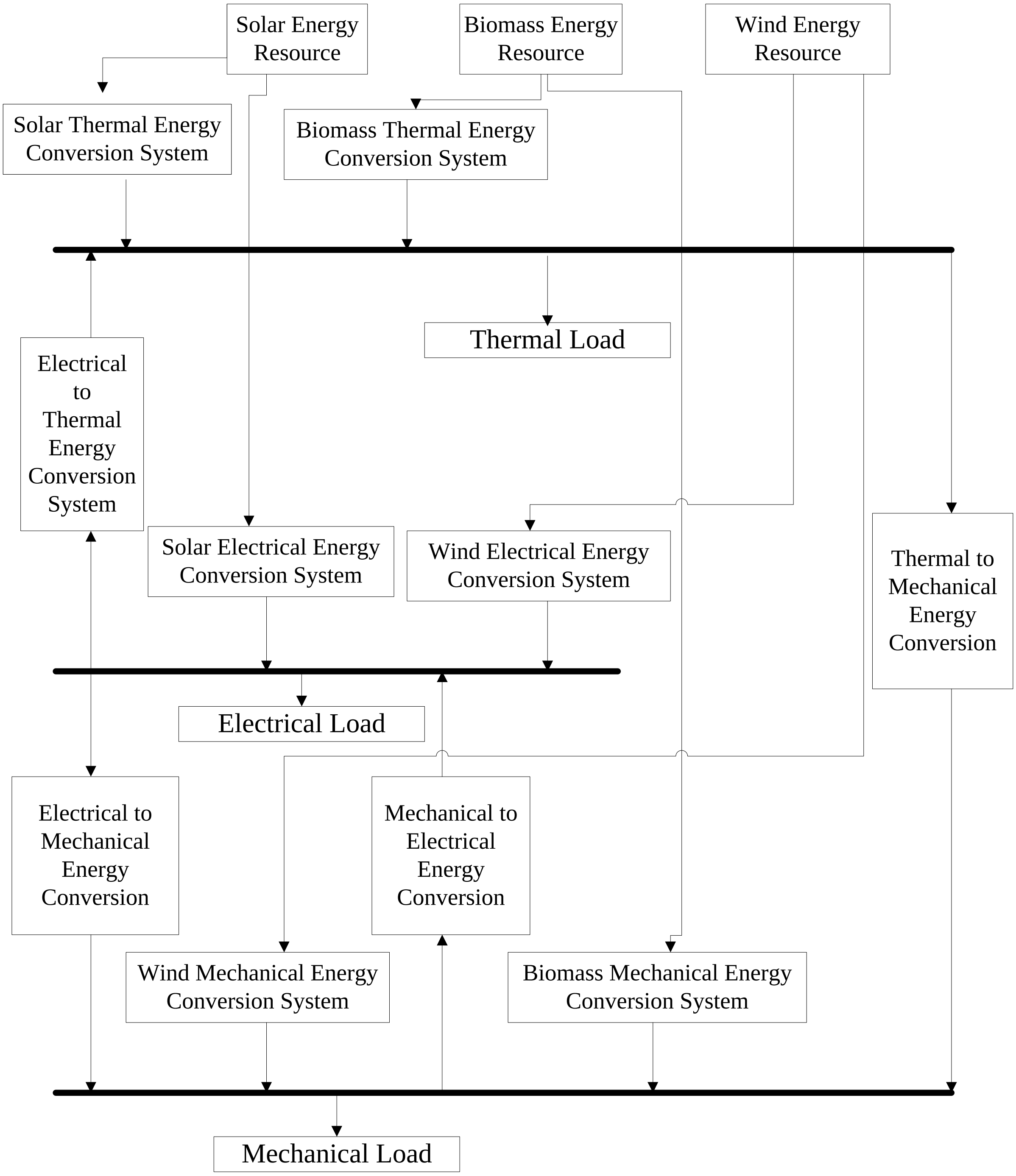


Fig. 4.1: Integrated Renewable Energy System

From the Fig.4.1, it can be inferred that the solar energy system can be able to supply the electrical demand and thermal demand with the help of photovoltaic panels and solar thermal collectors respectively. Similarly, wind energy system can supply the mechanical demand and electrical demand using appropriate conversion technology viz windmills, wind turbines. In addition, biomass energy system can supply thermal and mechanical demands. Considering conversion between different forms of energy, there are six possible combinations, namely, thermal to mechanical energy conversion, mechanical to thermal energy conversion, mechanical to electrical energy conversion, electrical to mechanical conversion, electrical to thermal energy conversion and thermal to electrical energy conversion. Among different combinations of energy conversion, two combinations i.e., mechanical to thermal and thermal to electrical are discarded on the grounds of the impractical and uneconomical techniques required to carry out the conversion.

In general, an availability factor is considered in the objective function for the availability of the appropriate conversion facility. The idea is to supply different energy demands as per the availability of resources at the cheapest operation cost. The following assumptions have been made to formulate the problem:

- The entire day is divided into several time segments of equal durations and the value of various variables involved in the problem are constant during the time segment under consideration.
- The sizes of energy conversion facilities are assumed to be fixed.
- The initial and final volumes of digester of biogas unit are known in prior.

Objective function

The objective is to minimize the operating cost of entire facility along with cost of unserved energy in order to supply different categories of demands considered in the study. Mathematically, it can be written as,

$$\text{Minimize } F = \sum_{\forall i} A_{ME} C_{ME} P_{ME}^{i} + \sum_{\forall i} C_{BT} P_{BT}^{i} + A_{ET} C_{ET} P_{ET}^{i} +$$

$$\sum_{\forall i} A_{EM} C_{EM} P_{EM}^{i} + A_{TM} C_{TM} P_{TM}^{i} + C_{BM} P_{BM}^{i} + C_{\alpha}(\alpha_{ML} + \alpha_{TL} + \alpha_{EL}) \qquad (4.7)$$

Here, subscript ME represents mechanical to electrical conversion, BT represents biomass to thermal energy conversion and ET denotes electrical to thermal energy conversion. Also, EM represents electrical to mechanical energy conversion, TM denotes thermal to mechanical energy conversion and BM represents biomass to mechanical energy conversion.

C_{XY} is the cost per unit kW of conversion of energy from Xth resource to Yth form and P_{XY}^{i} is the power generated in the ith time segment from Xth resource to Yth form. Also, $A_{MN} = \begin{cases} 0 \\ 1 \end{cases}$ depending upon the availability of M to N conversion technology for all resources viz Solar (S), Wind (W) and Biomass (B).

C_α denotes the cost of unserved energy. It is included to compel the facility to deliver at least minimum output power to the load. α_{ML} is the ratio of energy not served to the total mechanical load. Similarly, α_{TL} and α_{EL} are the ratios for thermal and electrical loads respectively.

Constraints

The following constraints have been considered to formulate the problem for obtaining the daily dispatch strategy of the IRES which is supplying the energy to a remote site.

Constraint of biomass energy balance

The energy from biomass is utilized to supply thermal demand by burning the biogas and mechanical demand by getting mechanical energy through a biogas based engine. The constraint for biogas is depicted in terms of volume of biogas utilized in a particular time segment. In other words, volume of biogas available in time segment i is the difference of the volume of biogas in the previous time segment and the volume utilized in the time segment. Mathematically, this can be written as:

$$v^i = v^{i-1} - \frac{P_{BT}^i}{\eta_{BT}^B CV} - \frac{P_{BM}^i}{\eta_{BM}^B CV} \qquad \forall i \tag{4.8}$$

where, v^i represents the volumes of biogas in the time segment i. P_{BT}^i is the output from biomass to thermal energy conversion facility in time segment i, CV is the calorific value of the biogas (kWh/m^3). P_{BM}^i is the output from biomass to mechanical energy conversion facility in time segment i.η_{BT} and η_{BM} are the conversion efficiencies of biomass to thermal and biomass to mechanical energy conversion facilities respectively.

Constraint of thermal demand balance

During the time segment, the total thermal energy supplied should be less than or equal to the thermal demand during that time segment. Mathematically, this can be written as:

$$P_{ST}^i + P_{BT}^i + P_{ET}^i - P_{TM}^i / \eta_{TM} \le P_{TL}^i \qquad \forall i \tag{4.9}$$

where, P_{ST}^i is the contribution from solar thermal energy conversion facility to meet the thermal load during time segment i, P_{ET}^i is the thermal energy through electrical thermal conversion during the time segment i and P_{BT}^{i} is the biogas thermal energy during that time segment. P_{TM}^{i} is the mechanical energy from thermal to mechanical energy conversion facility at time segment I and η_{TM} is the conversion efficiency from thermal to mechanical energy conversion. P_{TL}^{i} is the total thermal load during the time segment i.

Constraint of electrical demand balance

During the time segment, the total electrical energy supplied should be less than or equal to the electrical demand during that time segment. Mathematically, this can be written as:

$$P_{SE}^{i} + P_{WE}^{i} + P_{ME}^{i} - P_{EM}^{i} / \eta_{EM} - P_{ET}^{i} / \eta_{ET} \leq P_{EL}^{i} \qquad \forall i \tag{4.10}$$

where, P_{SE}^{i} is the contribution from SPV to meet electrical load during time segment i, P_{ME}^{i} is the electrical energy through mechanical electrical conversion during the time segment i and P_{WE}^{i} is the contribution from wind electrical energy conversion facility to meet electrical laod during that time segment. P_{EM}^{i} and P_{ET}^{i} represents the electrical energy consumed for mechanical and thermal energy conversion during time segment i. η_{EM} and η_{ET} are the conversion efficiencies of electrical to mechanical and electrical to thermal energy conversion facilities respectively. P_{EL}^{i} is the total electrical load during the time segment i.

Constraint of mechanical demand balance

Considering mechanical load as deferrable load, the total mechanical energy supplied should be less than or equal to the mechanical demand. Mathematically, this can be written as:

$$\sum_{\forall i}(P_{WM}^{i} + P_{BM}^{i} + P_{EM}^{i} + P_{TM}^{i} - P_{ME}^{i} / \eta_{ME}) \leq P_{ML} \qquad \forall i \qquad (4.11)$$

where, P_{WM}^{i} is the contribution from wind based mechanical energy conversion facility to meet mechanical demand during time segment i, P_{EM}^{i} is the mechanical energy through electrical-mechanical conversion during the time segment i, P_{BM}^{i} is the biomass based mechanical energy during time segment i and P_{TM}^{i} is the mechanical energy through thermal-mechanical conversion during the time segment i. P_{ME}^{i} represents the mechanical energy consumed for electrical conversion during that time segment. η_{ME} is the conversion efficiency of mechanical to electrical energy conversion facility. P_{ML}^{i} is the total mechanical load during time segment i.

<u>Constraint for checking out un-met load</u>

In order to keep a check on the energy not served (ENS), the ENS should be less than or equal to the different loads. For thermal load, it is given as:

$$ENS_{TL} \leq \sum_{\forall i} \alpha_{TL} . P_{TL}^{i} \qquad (4.12)$$

where, α_{TL} is the multiplying factor for the thermal load and it lies between 0 and 1.

The energy not served (ENS) is given by:

$$ENS_{TL} = \sum_{\forall i}(P_{ST}^{i} + P_{BT}^{i} + P_{ET}^{i} - P_{TM}^{i} / \eta_{TM} - P_{TL}^{i}) \qquad (4.13)$$

In the similar manner, for electrical load it is given as,

$$ENS_{EL} \leq \sum_{\forall i} \alpha_{EL} . P_{EL}^{i} \qquad (4.14)$$

where, ENS_{EL} is given as:

$$ENS_{EL} = \sum_{\forall i}(P_{SE}^{i} + P_{WE}^{i} + P_{ME}^{i} - P_{EM}^{i} / \eta_{EM} - P_{ET}^{i} / \eta_{ET} - P_{EL}^{i}) \qquad (4.15)$$

For mechanical load, it is given as:

$$ENS_{ME} \leq \sum_{\forall i} \alpha_{ML} . P_{ML}^{i} \tag{4.16}$$

where, ENS_{ML} is given as:

$$ENS_{ML} = \sum_{\forall i} (P_{WM}^{i} + P_{BM}^{i} + P_{EM}^{i} + P_{TM}^{i} - P_{ME}^{i} / \eta_{ME}) - P_{ML} \tag{4.17}$$

Upper and Lower Bounds on the variables

During each time segment, the power to be delivered is bounded by lower and upper limits. Since the contribution from SPV to meet electrical load cannot exceed the electrical energy available from it during a time segment. Hence, the following restriction must be maintained for each time segment:

$$0 \leq P_{SE}^{i} \leq P_{SPV}^{i} \qquad \forall i \tag{4.18}$$

where, P_{SPV}^{i} is the available electrical energy from SPV during the i^{th} time segment. Similarly, the contribution of wind energy for electrical energy cannot exceed the electrical energy available during a time segment. Hence, the following restriction must be maintained for each time segment:

$$0 \leq P_{WE}^{i} \leq P_{WTG}^{i} \qquad \forall i \tag{4.19}$$

where, P_{WTG}^{i} is the available electrical energy from WTG during the i^{th} time segment. In addition, the contribution of solar energy for thermal energy cannot exceed the thermal energy available from sun during a time segment. Hence, the following restriction must be maintained for each time segment:

$$0 \leq P_{ST}^{i} \leq P_{STH}^{i} \qquad \forall i \tag{4.20}$$

where, P_{STH}^{i} is the available thermal energy from solar collector during the ith time segment. Further, the thermal energy from biomass is also limited by its maximum limit during the ith time segment. Hence, the following restriction must be maintained for each time segment:

$$0 \le P_{BT}^{i} \le P_{BT\max} \qquad \forall i \qquad (4.21)$$

where, $P_{BT\max}$ is the rating of biomass to thermal energy conversion facility. Similarly, there are restrictions for a maximum thermal energy that can be extracted from electrical to thermal energy conversion. Mathematically, this can be written as:

$$0 \le P_{ET}^{i} \le P_{ET\max} \qquad \forall i \qquad (4.22)$$

where, $P_{ET\max}$ is the rating of electrical-thermal conversion during the ith time segment. Similarly, the contribution of wind energy for mechanical energy cannot exceed the maximum mechanical energy available from wind during a time segment. Hence, the following restriction must be maintained for each time segment:

$$0 \le P_{WM}^{i} \le P_{WMG}^{i} \qquad \forall i \qquad (4.23)$$

where, P_{WMG}^{i} is the available mechanical energy from WMG during the ith time segment. Further, the mechanical energy from biomass is also limited by its maximum limit during the ith time segment. Hence, the following restriction must be maintained for each time segment:

$$0 \le P_{BM}^{i} \le P_{BM\max} \qquad \forall i \qquad (4.24)$$

where, $P_{BM\max}$ is the rating of biomass to mechanical energy conversion facility. Similarly, there are restrictions for a maximum mechanical energy that can be extracted from electrical to mechanical energy conversion. Mathematically, this can be written as:

$$0 \le P_{EM}^{i} \le P_{EM\,\max} \qquad \forall i \tag{4.25}$$

where, $P_{EM\,\max}$ is the rating of electrical-mechanical conversion facility. Similarly, there are restrictions for a maximum electrical energy that can be extracted from mechanical to electrical energy conversion. Mathematically, this can be written as:

$$0 \le P_{ME}^{i} \le P_{ME\,\max} \qquad \forall i \tag{4.26}$$

where, $P_{ME\,\max}$ is the rating of mechanical-electrical conversion facility. The upper bounds for thermal to mechanical energy conversion is given as:.

$$0 \le P_{TM}^{i} \le P_{TM\,\max} \qquad \forall i \tag{4.27}$$

where, $P_{TM\,\max}$ is the rating of thermal – mechanical energy conversion facility. The volume of digester is bounded by its minimum and maximum limits. Mathematically, this can be written as:

$$v_{\min}^{i} \le v^{i} \le v_{\max}^{i} \qquad \forall i \tag{4.28}$$

where, $v_{\max}^{i}$ is the maximum volume of the biogas digester and $v_{\min}^{i}$ is the minimum volume of the digester.

Statement of the problem

Using Eqs. (4.7) – (4.28), the complete statement of the problem for daily scheduling of IRES to meet energy demand of a given site can be given as:

Minimize, $F = \sum_{\forall i} A_{ME} C_{ME} P_{ME}^{i} + \sum_{\forall i} C_{BT} P_{BT}^{i} + A_{ET} C_{ET} P_{ET}^{i} +$

$$\sum_{\forall i} A_{EM} C_{EM} P_{EM}^{i} + A_{TM} C_{TM} P_{TM}^{i} + C_{BM} P_{BM}^{i} + C_{\alpha} (\alpha_{ML} + \alpha_{TL} + \alpha_{EL}) \qquad (4.29)$$

Constraints

i) Biomass Energy

$$v^{i} = v^{i-1} - \frac{P_{BT}^{i}}{\eta_{BT}^{B} CV} - \frac{P_{BM}^{i}}{\eta_{BM}^{B} CV} \qquad \forall i \qquad (4.30)$$

ii) Thermal Generation-Demand In-equation

$$P_{ST}^{i} + P_{BT}^{i} + P_{ET}^{i} - P_{TM}^{i} / \eta_{TM} \le P_{TL}^{i} \qquad \forall i \qquad (4.31)$$

iii) Electrical Generation-Demand In-equation

$$P_{SE}^{i} + P_{WE}^{i} + P_{ME}^{i} - P_{EM}^{i} / \eta_{EM} - P_{ET}^{i} / \eta_{ET} \le P_{EL}^{i} \qquad \forall i \qquad (4.32)$$

iv) Mechanical Generation-Demand In-equation

$$\sum_{\forall i} (P_{WM}^{i} + P_{BM}^{i} + P_{EM}^{i} + P_{TM}^{i} - P_{ME}^{i} / \eta_{ME}) \le P_{ML} \qquad \forall i \qquad (4.33)$$

v) Un-met Thermal Load

$$ENS_{TL} \le \sum_{\forall i} \alpha_{TL} . P_{TL}^{i} \qquad (4.34)$$

vi) Un-met Electrical Load

$$ENS_{EL} \le \sum_{\forall i} \alpha_{EL} . P_{EL}^{i} \qquad (4.35)$$

vii) Un-met Mechanical Load

$$ENS_{ME} \le \sum_{\forall i} \alpha_{ML} . P_{ML}^{i} \qquad (4.36)$$

Upper and Lower Bounds

i) $0 \le P_{SE}^{i} \le P_{SPV}^{i} \quad \forall i$ (4.37)

ii) $0 \le P_{WE}^{i} \le P_{WTG}^{i} \quad \forall i$ (4.38)

iii) $0 \le P_{ST}^{i} \le P_{STH}^{i} \quad \forall i$ (4.39)

iv) $0 \le P_{BT}^{i} \le P_{BT\,\max} \quad \forall i$ (4.40)

v) $0 \le P_{ET}^{i} \le P_{ET\,\max} \quad \forall i$ (4.41)

vi) $0 \le P_{WM}^{i} \le P_{WMG}^{i} \quad \forall i$ (4.42)

vii) $0 \le P_{BM}^{i} \le P_{BM\,\max} \quad \forall i$ (4.43)

viii) $0 \le P_{EM}^{i} \le P_{EM\,\max} \quad \forall i$ (4.44)

ix) $0 \le P_{ME}^{i} \le P_{ME\,\max} \quad \forall i$ (4.45)

x) $0 \le P_{TM}^{i} \le P_{TM\,\max} \quad \forall i$ (4.46)

xi) $v_{\min}^{i} \le v^{i} \le v_{\max}^{i} \quad \forall i$ (4.47)

4.4 SOLUTION METHODOLOGY

For the optimal dispatch strategy for an IRES, problem has been formulated and presented through eqs.(4.29)-(4.47) with the objective of minimum operating cost along with cost o energy not served. The developed formulation is a linear programming problem. In this work, this problem has been solved by Linear Programming (LP) technique using MATLAB Optimization Toolbox, which is based on LIPSOL (Mathworks, USA; Zhang, 1995). It uses Primal-Dual Interior-Point method (Mathworks, USA; Malhotra, 1995; Zhang, 1995). to solve the large-scale linear optimization problems. From the formulation, it is clear that there are a total number of

266 variables with 23 equality constraints and 52 inequality constraints. Various computational steps involved in the solution of the daily scheduling problem given by (4.29) to (4.47), are as follows:

- Read the following data:
    a. Ratings of all energy conversion facilities and efficiencies of inter-energy conversion facilities.
    b. Minimum, maximum, initial and final volumes of biogas digester.
    c. Number of time segments and corresponding electrical, mechanical, thermal load and wind speed, solar radiations data for the day under consideration,
    d. Operating cost of biomass to thermal, biomass to mechanical, mechanical to electrical, electrical to mechanical and electrical to thermal energy conversion facility.
- Calculate the power output from different renewable energy resources based conversion facilities as discussed in section 4.2.
- Solve the daily scheduling problem, given by (4.29)-(4.47), using Linear Programming technique and store the obtained results.

4.5 RESULTS AND DISCUSSION

In order to test the developed formulation, the developed model has been applied to the specified site. The description of the site is given in Chapter 2. To develop the daily operational strategy, a typical day of the month of January has been chosen. The solar radiations and wind speeds values as obtained from the ANN for the typical day is shown in Fig. 4.2.

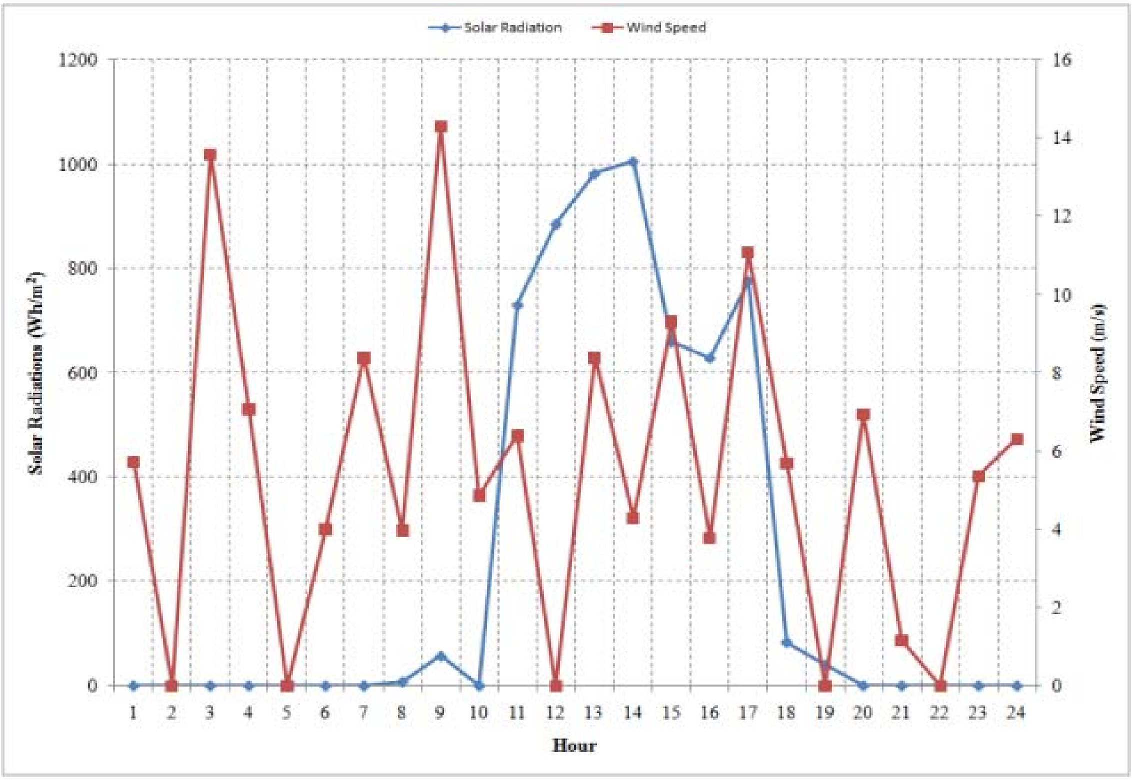


Fig. 4.2: Predicted hourly solar radiations and wind speeds

The sizes of different energy conversion facilities considered in this study are given in Table 4.1.

Table 4.1: Sizes of different energy conversion facilities

Energy Conversion Facility	**Sizes**
Solar-Electrical Conversion Facility	8 kW
Wind – Electrical Conversion Facility	10 kW
Mechanical- Electrical Conversion Facility	25 kW
Solar- Thermal Conversion Facility	3 kW
Biomass – Thermal Conversion Facility	3 kW
Electrical-Thermal Conversion Facility	3 kW
Wind Mechanical Conversion Facility	25 kW
Biomass Mechanical	5 kW
Electrical-Mechanical	7 kW

The conversion efficiencies like electrical-thermal, mechanical-electrical, electrical – mechanical and thermal -mechanical are taken as 0.3, 0.32, 0.55 and 0.25 respectively and their respective per unit cost of production is Rs. 1.1, 0.35 and 2.125 (Gupta et al., 2010).

The MATLAB codes are run to obtain the values of power supplied through various resources. Fig. 4.3 shows the electrical power output from different resources and the electrical load.

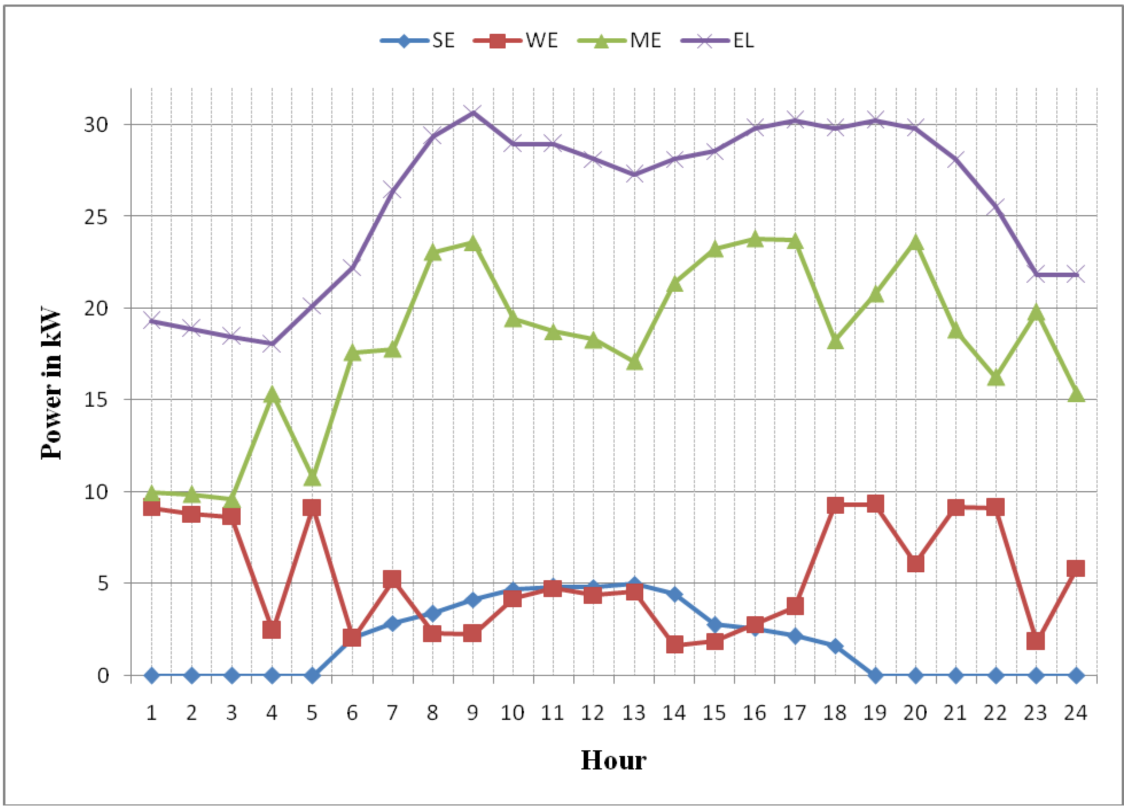


Fig. 4.3: Electrical Power Generation via various resources along with electrical load

It is clear from Fig. 4.3 that solar and wind energy complements each other. During the un-availability of wind energy, the electrical demand is supplied through biomass generator in addition to solar panels.

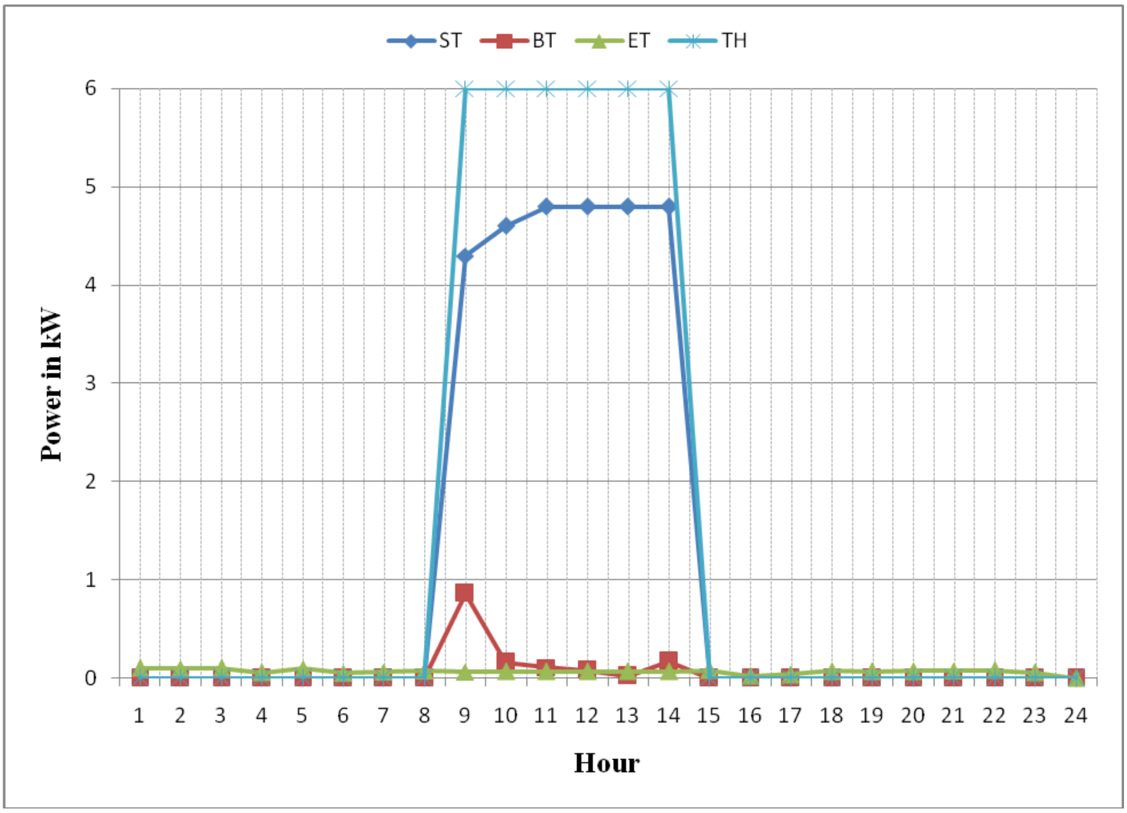


Fig. 4.4: Thermal Power Generation via various resources along with thermal load

As it is clear from Fig. that solar energy is available for most part of the day, thermal energy demand (cooking demand) can be met by solar energy in conjunction with biogas plant (Fig. 4.4).

Similar is the case with mechanical demand, mechanical energy produced from biomass and wind energy resources. A mechanical power of around 1.5 kW is available through out the day and is sufficient to supply the mechanical load of water pumping in any hour of the day (Fig. 4.5).

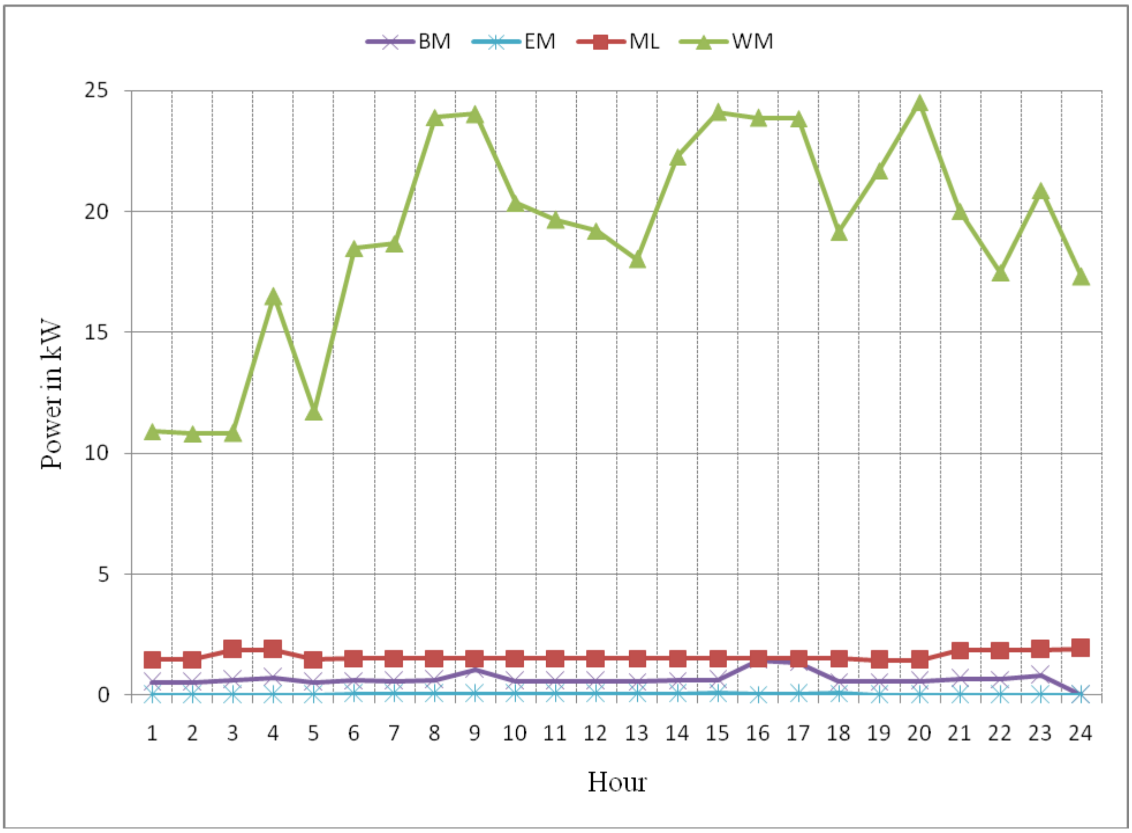


Fig. 4.5: Mechanical Power Generation via various resources along with mechanical load

Fig. 4.5 clearly depicts the complementarities of wind and biomass energy resources. It can also be seen that the mechanical load for the day is very low when compared with the amount of mechanical power generated. The mechanical power generated is also supplying the electrical power through mechanical to electrical conversion facility. It was also found that the value of the objective function, that is, the total operation cost of the system for the day is Rs. 1919.20.

To analyze the deficit in the power supplied, the value of energy not served has been plotted for a value α_{TH} for thermal load and the value of α_{EL} for electrical load. The hourly variation of thermal power not served is shown in Fig. 4.6.

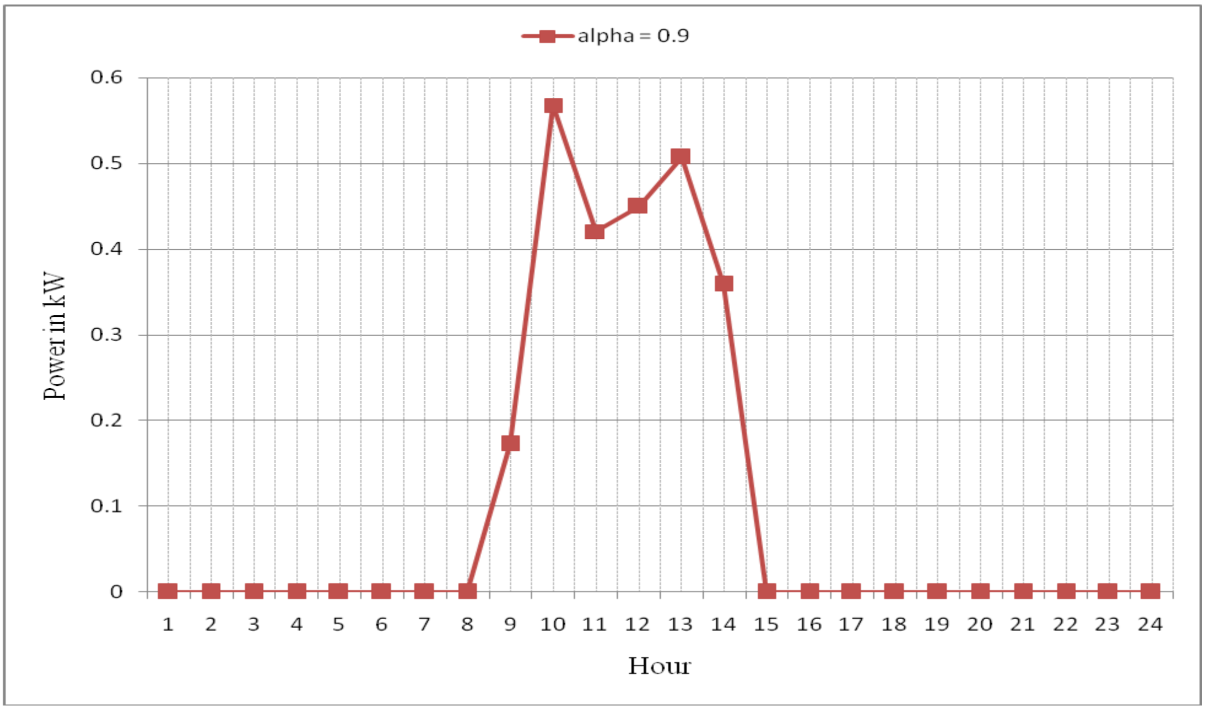


Fig. 4.6: Hourly unserved thermal power variation with alpha (α_{TH})

It is evident from Fig. 4.6 that a value of 0.56 kW of thermal load gets unserved when α_{TL} is near to unity. The hourly variation of electrical power not served is shown in Fig. 4.7.

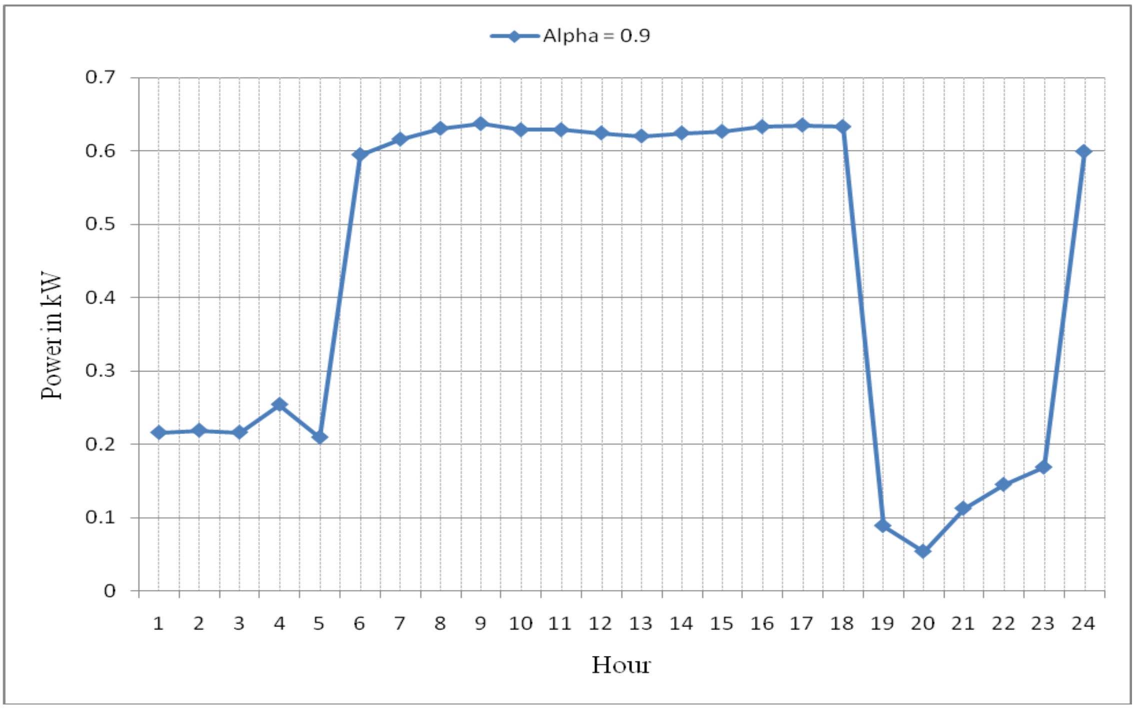


Fig. 4.7: Hourly unserved thermal power variation with alpha (α_{EL})

It is clear from the Fig. 4.7 that the value of 0.63 kW of electrical energy remains unserved for a typical day.

4.6 CONCLUSION

In this chapter, an optimization problem for obtaining an operational strategy for the operation of different renewable energy resources in tandem has been formulated. The different resources included were solar, wind and biomass. The data for these resources has been predicted in a day-ahead scenario in the previous chapter. For optimal operational strategy, the operating cost has been minimized. Various resource-generation and demand-balance constraints are considered for obtaining an optimal point. The formulated problem has been solved through Linear Programming technique using MATLAB optimization toolbox. From the results obtained, following conclusions can be drawn:

- When the IRES is run on the day-ahead scenario for minimum operating cost, the demands are met through the resources which are available at the time and having the minimum operating cost. In case of electrical, the wind and the mechanical-electrical conversion facility complement each other. In case of thermal demand, solar and biogas complement each other. For mechanical demand being deferable, it is easily supplied throughout the day. The energy generated through various conversions collectively supply the demands.

- It can also be seen that the system is sufficient to supply the demands of the site. When the results are analyzed, in terms of the variation of alpha (α) for both thermal and electrical demands. It was found that for α=0.9, 056 kW and

0.63kW of thermal and electrical power respectively remains unserved for the typical day.

A more generalized study needs to be made. In addition to operation cost, there is a scope of optimization of capital cost in case of a system in planning stage. To develop a more reliable system and ensure continuous energy availability, there is a scope of reliability study of this system.

CHAPTER-5

OPTIMAL SIZING OF THE SYSTEM

5.1 GENERAL

The designing of autonomous integrated systems utilizing locally available renewable energy resources particularly solar and wind is a complicated task. The intermittency of these resources acts adversely and makes the task more tedious. If the system is designed well, it provides a reliable service, fuel free supply and can even operate unattended for extended periods of time.

It has also been found in the literature that only limited experience exists with the operation of integrated systems comprising of PV, wind and biomass energy sources. On the one hand, the integration of these resources provides the clear benefits of exploiting the complementarity of different resources. On the other hand, there are problems which emerge from the increased complexity of the system in comparison with the case of each generator operating alone. This opens different avenues for research to improve the system design.

An important aspect of this design is sizing. Correct sizing of the stand-alone integrated solar, wind and biomass based systems has been recognized as crucial in order to provide a reliable power at an optimum cost.

Sizing of any system is defined as the determination of capacities of different generators used in the system keeping installation and operation cost into consideration. While determining the optimum sizes, there is always a trade-off between the cost of the system and the reliability of the system. When designing in rural aspects, cost is given an upper hand over reliability of the system. As mentioned, this cost comprises of installation and operation cost. Therefore, the total cost can further be minimized if a proper optimum operational strategy has been coined out prior to the determination of sizes of different generators. The determination of optimum operational strategy has been discussed in previous chapter.

Various work has been reported on the sizing of different generators (Borowy and Salameh, 1996; Chedid and Rahman, 1997; Dufo-Lopez et al., 2007; Dursun et al., 2011; Gupta et al., 2010; Kaldellis et al., 2007; Karaki et al., 2000; Nehrir et al., 2000; Sinha, 1993 and Yang et al., 2008). Most of the work reported in the planning of IRES was focused on the sizing of resources. As far as planning of integrated system is concerned, besides sizing, the operational strategy play an important role in analyzing the economics of the system. This left a substantial scope for the development of time-ahead operational strategy with the application of time series modeling of solar and wind energy resources. In addition, Different hybrid techniques have been discussed in the literature. The application of these techniques was limited to sizing problems. This opened up a good amount of scope for hybrid techniques for the optimal planning of integrated renewable energy systems.

In this chapter, the problem has been formulated with the combination of operation as well as installation cost. A hybrid optimization approach has been proposed for the optimum design of the system. This hybrid approach covers the advantages of evolutionary programming and linear programming techniques. Sizing problem, being a discrete search problem, has been solved through evolutionary programming and operation strategy determination, being a continuous problem, has been solved through linear programming technique.

5.2 PROBLEM FORMULATION

As discussed in previous chapters, the overall demands of a rural area are divided into three categories, that are, thermal, electrical and mechanical. Referring to the system shown in Fig. 4.1, the solar energy system is considered for supplying the electrical demand, thermal demand and mechanical demand with the help of photovoltaic panels, solar thermal collectors and photovoltaic panels in conjunction with electrical generators respectively. Similarly, wind energy system is considered for supplying the mechanical demand, electrical demand and thermal demand if appropriate conversion technology viz windmills, wind turbines and electric heaters are available. In addition, biomass energy system is considered for supplying thermal, mechanical and electrical demands if appropriate conversion facility is available.

In order to work out the total cost of the system, it is necessary to evaluate the capital cost as well as the operational cost. The capital cost includes the cost incurred in the installation of the facility. It depends upon the sizes of different energy generators. Following a practical approach, the sizes of different energy generators available in the market are considered in the problem. The available sizes are discrete in nature.

In addition, the study period is of one year which is divided into four seasons. Each season is characterized by a typical day.

While designing the overall system, it is necessary to consider the possible interactions within different set of demands. For example, if a proper conversion device is available then the thermal needs can also be fulfilled by the electrical power generated, if in excess, from wind. Therefore, to design the overall system should be designed by considering the similar logic for all set of demands.

The objective function will be the total cost of the system inclusive of installation and operation cost. If ST_{AV} are number of options for solar-thermal energy conversion, the total capital cost for this can be written as:

$$\sum_{m=1}^{ST_{AV}} N_{ST,m}.CC_{ST,m} \tag{5.1}$$

where, $N_{ST,m}$ is the number of m^{th} solar thermal energy conversion facility and $CC_{ST,m}$ is the cost of installation of m^{th} solar thermal energy conversion facility Similarly, if BT_{AV} are the number of options for biomass-thermal energy conversion, the total capital cost for this can be written as:

$$\sum_{m=1}^{BT_{AV}} N_{BT,m}.CC_{BT,m} \tag{5.2}$$

where, $N_{BT,m}$ is the number of m^{th} biomass-thermal energy conversion facility and $CC_{BT,m}$ is the cost of installation of m^{th} biomass-thermal energy conversion facility. Similarly, if electrical to thermal conversion facility is available and ET_{AV} are the number of options for electrical – thermal energy conversion, the total capital cost for this can be written as:

$$\sum_{m=1}^{ET_{AV}} A_{ET}.N_{ET,m}.CC_{ET,m} \tag{5.3}$$

where, A_{ET} denotes the availability factor and can have a value either 0 or 1, Availability factor, considered here, implies whether a particular conversion facility is available or not. The value of availability factor may either be zero or one. $N_{ET,m}$ is the number of m^{th} electrical – thermal conversion facility with $CC_{ET,m}$ is the cost of installation of m^{th} electrical – thermal conversion facility. In the similar manner, if SE_{AV} are the number of options for solar – electrical energy conversion, the total capital cost for this can be written as:

$$\sum_{n=1}^{SE_{AV}} N_{SE,n}.CC_{SE,n} \tag{5.4}$$

where, $N_{SE,n}$ is the number of n^{th} solar-electrical energy conversion facility and $CC_{SE,n}$ is the cost of installation of n^{th} solar-electrical energy conversion facility. Now, if WE_{AV} are the number of options for wind – electrical energy conversion, the total capital cost for this can be written as:

$$\sum_{n=1}^{WE_{AV}} N_{WE,n}.CC_{WE,n} \tag{5.5}$$

where, $N_{WE,n}$ is the number of n^{th} wind-electrical energy conversion facility and $CC_{WE,n}$ is the cost of installation of n^{th} wind-electrical energy conversion facility. If mechanical to electrical conversion facility is available and ME_{AV} are the number of options for mechanical -electrical energy conversion, the total capital cost for this can be written as:

$$\sum_{n=1}^{ME_{AV}} A_{ME}.N_{ME,n}.CC_{ME,n} \tag{5.6}$$

where, A_{ME} denotes the availability factor, $N_{ME,n}$ is the number of n^{th} mechanical – electrical conversion facility with $CC_{ME,n}$ is the cost of installation of n^{th} mechanical – electrical conversion facility. In the similar manner, if WM_{AV} are the number of options for wind-mechanical energy conversion, the total capital cost for this can be written as:

$$\sum_{r=1}^{WM_{AV}} N_{WM,r}.CC_{WM,r} \tag{5.7}$$

Where, $N_{WM,r}$ is the number of r^{th} wind-mechanical energy conversion facility and $CC_{WM,r}$ is the cost of installation of r^{th} wind-mechanical energy conversion facility. Similarly, if BM_{AV} are the number of options for biomass-mechanical energy conversion, the total capital cost for this can be written as:

$$\sum_{r=1}^{BM_{AV}} N_{BM,r}.CC_{BM,r} \tag{5.8}$$

where, $N_{BM,r}$ is the number of r^{th} biomass-mechanical energy conversion facility and $CC_{BM,r}$ is the cost of installation of r^{th} biomass-mechanical energy conversion facility. If thermal-mechanical conversion facility is available and TM_{AV} are the number of options for thermal-mechanical energy conversion, the total capital cost for this can be written as:

$$\sum_{r=1}^{TM_{AV}} A_{TM}.N_{TM,r}.CC_{TM,r} \tag{5.9}$$

where, A_{TM} denotes the availability factor, $N_{TM,r}$ is the number of r^{th} thermal-mechanical conversion facility with $CC_{TM,r}$ is the cost of installation of r^{th} thermal-mechanical conversion facility. Also, if electrical-mechanical conversion facility is available and EM_{AV} are the number of options for electrical -mechanical energy conversion, the total capital cost for this can be written as:

$$\sum_{r=1}^{EM_{AV}} A_{EM}.N_{EM,r}.CC_{EM,r} \tag{5.10}$$

where, A_{EM} denotes the availability factor, $N_{EM,r}$ is the number of r^{th} electrical - mechanical conversion facility with $CC_{EM,r}$ is the cost of installation. Hence, total capital cost is given by:

$$\sum_{m=1}^{ST_{AV}} N_{ST,m}.CC_{ST,m} + \sum_{m=1}^{BT_{AV}} N_{BT,m}.CC_{BT,m} + \sum_{m=1}^{ET_{AV}} A_{ET}.N_{ET,m}.CC_{ET,m} + \sum_{n=1}^{SE_{AV}} N_{SE,n}.CC_{SE,n} +$$
$$\sum_{n=1}^{WE_{AV}} N_{WE,n}.CC_{WE,n} + \sum_{n=1}^{ME_{AV}} A_{ME}.N_{ME,n}.CC_{ME,n} + \sum_{r=1}^{WM_{AV}} N_{WM,r}.CC_{WM,r} + \sum_{r=1}^{BM_{AV}} N_{BM,r}.CC_{BM,r} +$$
$$\sum_{r=1}^{TM_{AV}} A_{TM}.N_{TM,r}.CC_{TM,r} + \sum_{r=1}^{EM_{AV}} A_{EM}.N_{EM,r}.CC_{EM,r} \tag{5.11}$$

The operation cost of the system for all seasons can be written as:

$$\sum_{s=1}^{4}\sum_{t=1}^{24}[\sum_{m=1}^{BT_{AV}} P_{BT,m}(s,t).OC_{BT,m} + \sum_{m=1}^{ET_{AV}} P_{ET,m}(s,t).OC_{ET,m} + \sum_{n=1}^{ME_{AV}} P_{ME,n}(s,t).OC_{ME,n} +$$

$$+\sum_{r=1}^{BM_{AV}} P_{BM,r}(s,t).OC_{BM,r} + \sum_{r=1}^{TM_{AV}} P_{TM,r}(s,t).OC_{TM,r} + \sum_{r=1}^{EM_{AV}} P_{EM,r}(s,t).OC_{EM,r}\ ].N_{s}+$$

$$C_{\alpha}(\alpha_{ML}+\alpha_{TL}+\alpha_{EL}) \tag{5.12}$$

Here, N_s is the number of days in a season. $P_{ET,m}(s,t)$ represents the total power generated from the m^{th} electrical conversion facility to thermal energy during hour t of season s with an operating cost of $OC_{ET,m}$. Similarly, $P_{ME,n}(s,t)$ denotes the total power from n^{th} mechanical to electrical energy conversion facility during hour t of season s. The cost of operation of converting mechanical energy into electrical energy is taken as $OC_{ME,n}$. $P_{TM,r}(s,t)$ is the total power from r^{th} thermal to mechanical conversion facility during hour t of season s. Hence, the total cost will be the summation of installation cost and operation cost and is given as:

$$\sum_{m=1}^{ST_{AV}} N_{ST,m}.CC_{ST,m} + \sum_{m=1}^{BT_{AV}} N_{BT,m}.CC_{BT,m} + \sum_{m=1}^{ET_{AV}} A_{ET}.N_{ET,m}.CC_{ET,m} + \sum_{n=1}^{SE_{AV}} N_{SE,n}.CC_{SE,n} +$$

$$\sum_{n=1}^{WE_{AV}} N_{WE,n}.CC_{WE,n} + \sum_{n=1}^{ME_{AV}} A_{ME}.N_{ME,n}.CC_{ME,n} + \sum_{r=1}^{WM_{AV}} N_{WM,r}.CC_{WM,r} + \sum_{r=1}^{BM_{AV}} N_{BM,r}.CC_{BM,r} +$$

$$\sum_{r=1}^{TM_{AV}} A_{TM}.N_{TM,r}.CC_{TM,r} + \sum_{r=1}^{EM_{AV}} A_{EM}.N_{EM,r}.CC_{EM,r} + \sum_{s=1}^{4}\sum_{t=1}^{24}[\sum_{m=1}^{BT_{AV}} P_{BT,m}(s,t).OC_{BT,m} +$$

$$\sum_{m=1}^{ET_{AV}} P_{ET,m}(s,t).OC_{ET,m} + \sum_{n=1}^{ME_{AV}} P_{ME,n}(s,t).OC_{ME,n} ++ \sum_{r=1}^{BM_{AV}} P_{BM,r}(s,t).OC_{BM,r} +$$

$$\sum_{r=1}^{TM_{AV}} P_{TM,r}(s,t).OC_{TM,r} + \sum_{r=1}^{EM_{AV}} P_{EM,r}(s,t).OC_{EM,r}\ ].\ N_{s} \qquad + C_{\alpha}(\alpha_{ML}+\alpha_{TL}+\alpha_{EL})$$

(5.13)

Eq. (5.13) represents the objective function for the overall system. This objective function is to be minimized subject to certain constraints. The energy output from the available thermal energy generators for the particular time t should be less than the total thermal energy demand of that period as shown in Eq. (5.14)

$$\sum_{m=1}^{ST_{AV}} .P_{ST,m}^{TH}(s,t) + \sum_{m=1}^{BT_{AV}} .P_{BT,m}^{TH}(s,t) + \sum_{m=1}^{ET_{AV}} A_{ET}.P_{ET,m}^{TH}(s,t) - \sum_{r=1}^{TM_{AV}} A_{TM}.P_{TM,r}^{ML}(s,t)/\eta_{TM} \le P_{TH}(s,t) \quad (5.14)$$

with, s=1 to 4 and t = 1 to 24

Similarly, the energy output from the available electrical energy generators for the particular time t should be less than the total electrical energy demand of that period as shown in Eq. (5.15)

$$\sum_{n=1}^{SE_{AV}} .P_{SE,n}^{EL}(s,t) + \sum_{n=1}^{WE_{AV}} .P_{WE,n}^{EL}(s,t) + \sum_{n=1}^{ME_{AV}} A_{ME} P_{ME,n}^{EL}(s,t) -$$

$$\sum_{r=1}^{EM_{AV}} A_{EM}.P_{EM,r}^{ME}(s,t)/\eta_{EM} - \sum_{m=1}^{ET_{AV}} A_{ET}.P_{ET,m}^{TH}(s,t)\eta_{ET} \le P_{EL}(s,t) \quad (5.15)$$

where, s=1 to 4 and t = 1 to 24. And, the energy output from the available mechanical energy generators for the particular time t should be less than the total mechanical energy demand of that period as shown in Eq. (5.16).

$$\sum_{t=1}^{24}\Big(\sum_{r=1}^{WM_{AV}} P_{WM,r}^{ML}(s,t) + \sum_{r=1}^{BM_{AV}} P_{BM,r}^{ML}(s,t) + \sum_{r=1}^{TM_{AV}} A_{TM}.P_{TM,r}^{ML}(s,t) +$$

$$\sum_{r=1}^{EM_{AV}} A_{EM}.P_{EM,r}^{ML}(s,t) - \sum_{n=1}^{ME_{AV}} A_{ME}.P_{ME,n}^{EL}(s,t)/\eta_{ME}\Big) \le P_{ML}(s) \quad (5.16)$$

Also, volume of biogas available in time segment t is the difference of the volume of biogas in the previous time segment and the volume utilized in the time segment.

$$v(s,t) \; = v(s,t-1) - \sum_{m=1}^{BT_{AV}} \frac{P_{BT,m}(s,t)}{\eta_{BT,m}CV} - \sum_{r=1}^{BM_{AV}} \frac{P_{BM,r}(s,t)}{\eta_{BM,r}CV} \tag{5.17}$$

The energy not served for thermal load can be written as:

$$\begin{aligned} ENS_{TL} = \alpha_{TL}.\sum_{s=1}^{4} \sum_{t=1}^{24} (\sum_{m=1}^{ST_{AV}} .P_{ST,m}^{TH}(s,t) + \sum_{m=1}^{BT_{AV}} .P_{BT,m}^{TH}(s,t) + \\ \sum_{m=1}^{ET_{AV}} A_{ET}.P_{ET,m}^{TH}(s,t) - \sum_{r=1}^{TM_{AV}} A_{TM}.P_{TM,r}^{ML}(s,t)/\eta_{TM} - P_{TH}(s,t)) \end{aligned} \tag{5.18}$$

The energy not served for electrical load can be written as:

$$\begin{aligned} ENS_{EL} = \alpha_{EL}.\sum_{s=1}^{4}\sum_{t=1}^{24}(\sum_{n=1}^{SE_{AV}} .P_{SE,n}^{EL}(s,t) + \sum_{n=1}^{WE_{AV}} .P_{WE,n}^{EL}(s,t) + \sum_{n=1}^{ME_{AV}} A_{ME} P_{ME,n}^{EL}(s,t) - \\ \sum_{r=1}^{EM_{AV}} A_{EM}.P_{EM,r}^{ME}(s,t)/\eta_{EM} - \sum_{m=1}^{ET_{AV}} A_{ET}.P_{ET,m}^{TH}(s,t)\eta_{ET} - P_{EL}(s,t) \end{aligned} \tag{5.19}$$

The energy not served for mechanical load can be written as:

$$\begin{aligned} ENS_{ML} = \alpha_{ML}\sum_{s=1}^{4}\sum_{t=1}^{24}(\sum_{r=1}^{WM_{AV}} P_{WM,r}^{ML}(s,t) + \sum_{r=1}^{BM_{AV}} P_{BM,r}^{ML}(s,t) + \sum_{r=1}^{TM_{AV}} A_{TM}.P_{TM,r}^{ML}(s,t) + \\ \sum_{r=1}^{EM_{AV}} A_{EM}.P_{EM,r}^{ML}(s,t) - \sum_{n=1}^{ME_{AV}} A_{ME}.P_{ME,n}^{EL}(s,t)/\eta_{ME} - P_{ML}(s) \end{aligned} \tag{5.20}$$

Upper and Lower Bounds

The total power from m^{th} solar thermal energy conversion facility is bound in between 0 and the total power available multiply by the total number of m units. Mathematically this can be written as:

$$0 \le P_{ST,m}(s,t) \le P_{STH}(s,t).N_{ST,m} \tag{5.21}$$

Similarly, the upper limit for the thermal power generated from the m^{th} electrical-thermal energy conversion facility is the rating of m^{th} unit multiply by the total number of m units. The lower bound for this is 0. Mathematically, this can be written as:

$$0 \le P_{ET,m}(s,t) \le P_{ET,m}.N_{ET,m} \tag{5.22}$$

In the similar manner, the total power from m^{th} biomass thermal energy conversion facility is bound in between 0 and rating of m^{th} unit multiply by the total number of m units. Mathematically this can be written as:

$$0 \le P_{BT,m}(s,t) \le P_{BT,m}.N_{BT,m} \tag{5.23}$$

Now, the total electrical power from the n^{th} solar electrical energy conversion facility lies in between 0 and the total power available times the total number of n units. Mathematically this can be written as:

$$0 \le P_{SE,n}(s,t) \le P_{SPV}(s,t).N_{SE,n} \tag{5.24}$$

Similarly, the upper limit for the electrical power generated from the n^{th} wind-electrical energy conversion facility is the total available multiply by the total number of n units. The lower bound for this is 0. Mathematically, this can be written as:

$$0 \le P_{WE,n}(s,t) \le P_{WTG}(s,t).N_{WE,n} \tag{5.25}$$

The total power from n^{th} mechanical to electrical conversion facility is bound between 0 and the rating of n^{th} facility multiply by the total number of *n* facilities. Mathematically this can be written as:

$$0 \le P_{ME,n}(s,t) \le P_{ME,n}.N_{ME,n} \tag{5.26}$$

Similarly, the upper limit for the mechanical power generated from the r^{th} wind-mechanical energy conversion facility is the total power available multiply by the total number of r units. The lower bound for this is 0. Mathematically, this can be written as:

$$0 \leq P_{WM,r}(s,t) \leq P_{WMG}(s,t).N_{WM,r} \tag{5.27}$$

The total power from r^{th} biomass to mechanical conversion facility is bound between 0 and the rating of r^{th} facility multiply by number of *r* facilities. Mathematically this can be written as:

$$0 \leq P_{BM,r}(s,t) \leq P_{BM,r}.N_{BM,r} \tag{5.28}$$

In the similar manner, the upper bound for the mechanical power generated from the r^{th} electrical-mechanical energy conversion facility is the rating of r^{th} unit multiply by the total number of r units. The lower bound for this is 0. Mathematically, this can be written as:

$$0 \leq P_{EM,r}(s,t) \leq P_{EM,r}.N_{EM,r} \tag{5.29}$$

The total power from r^{th} thermal to mechanical conversion facility is bound between 0 and the rating of r^{th} facility multiply by number of *r* facilities. Mathematically this can be written as:

$$0 \leq P_{TM,r}(s,t) \leq P_{TM,r\_}.N_{TM,r} \tag{5.30}$$

The total number of sizes of solar thermal energy conversion facility is bound in between 0 and $N_{ST,m}^{\max}$. Mathematically, this can be written as:

$$0 \leq N_{ST,m} \leq N_{ST,m}^{\max} \tag{5.31}$$

The total number of sizes of electrical thermal energy conversion facility is bound in between 0 and $N_{ET,m}^{\max}$. Mathematically, this can be written as:

$$0 \le N_{ET,m} \le N_{ET,m}^{\max} \tag{5.32}$$

The total number of sizes of biomass-thermal energy conversion facility considered in this study is $N_{BT,m}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{BT,m} \le N_{BT,m}^{\max} \tag{5.33}$$

The total number of sizes of solar-electrical energy conversion facility considered in this study is $N_{SE,n}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{SE,n} \le N_{SE,n}^{\max} \tag{5.34}$$

The total number of sizes of wind-electrical energy conversion facility considered in this study is $N_{WE,n}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{WE,n} \le N_{WE,n}^{\max} \tag{5.35}$$

The total number of sizes of mechanical-electrical energy conversion facility considered in this study is $N_{ME,n}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{ME,n} \le N_{ME,n}^{\max} \tag{5.36}$$

Similarly, the total number of sizes of wind-mechanical energy conversion facility considered in this study is $N_{WM,r}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{WM,r} \le N_{WM,r}^{\max} \tag{5.37}$$

In the similar manner, the total number of sizes of biomass-mechanical energy conversion facility considered in this study is $N_{BM,r}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{BM,r} \le N_{BM,r}^{\max} \tag{5.38}$$

Similarly, the total number of sizes of electrical-mechanical energy conversion facility considered in this study is $N_{EM,r}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{EM,r} \le N_{EM,r}^{\max} \tag{5.39}$$

The total number of sizes of thermal-mechanical energy conversion facility considered in this study is $N_{TM,r}^{\max}$. Hence, the expression for upper and lower bounds can be written as:

$$0 \le N_{TM,r} \le N_{TM,r}^{\max} \tag{5.40}$$

5.3 SOLUTION METHODOLOGY

The developed formulation is a combination of two interdependent problems. One is sizing and the other is operational strategy optimization. The optimal sizing of renewable energy generators is a non-differentiable type of formulation, as the search space is discontinuous or discrete. Classical optimization techniques are not appropriate for this type of problem. Hence, evolutionary programming (EP) based algorithm is used for the solution of these type of problems. EP based techniques is similar to evolutionary strategy and genetic algorithm. It works by generating a population of solutions towards the global minimum through the use of mutation operator and selection scheme. As the function of optimum operational strategy is continuous and differentiable, classical technique like linear programming (LP) will hold good. A brief description of EP algorithm has been presented in Appendix – A.

For the proposed hybrid algorithm, the following computational steps are performed to solve the formulated problem:

Generation of initial population

As a first step, a population of individuals has been generated. The individuals represent a feasible solution. In the given problem, each individual represents the number of different energy conversion facilities. The considered sizes of different energy conversion facilities have been indexed by consecutive integers starting from 1. The initial population (IP) is generated randomly by drawing a uniformly distributed random number between the minimum and maximum values of indices and is given by the following expression:

$$IP_{ij} = \begin{cases} Round[U_{0,1} \times N^{\max}_{ST,j}] & j = 1 to ST_{AV} \\ Round[U_{0,1} \times N^{\max}_{BT(j-ST_{AV})}] & j = ST_{AV} + 1 to ST_{AV} + BT_{AV} \\ Round[U_{0,1)} \times N^{\max}_{ET(j-ST_{AV}-BT_{AV})}] & j = ST_{AV} + BT_{AV} + 1 to ST_{AV} + BT_{AV} + ET_{AV} \\ Round[U_{0,1} \times N^{\max}_{SE(j-ST_{AV}-BT_{AV}-ET_{AV})}] & j = ST_{AV} + BT_{AV} + ET_{AV} + 1 to ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} \\ Round[U_{0,1} \times N^{\max}_{WE(j-ST_{AV}-BT_{AV}-ET_{AV}-SE_{AV})}] & j = ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} + 1 to ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} \\ & + WE_{AV} \\ . & . \\ . & . \\ . & . \\ . & . \\ Round[U_{0,1} \times N^{\max}_{EM(j-ST_{AV}-BT_{AV}-ET_{AV}-SE_{AV}-WE_{AV}-ME_{AV}-WM_{AV}-BM_{AV}-TM_{AV})}] & j = ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} + WE_{AV} + ME_{AV} + WM_{AV} \\ & + BM_{AV} + TM_{AV} + 1 to ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} \\ & + WE_{AV} + ME_{AV} + WM_{AV} + BM_{AV} + TM_{AV} + EM_{AV} \end{cases} \tag{5.41}$$

where, IP_{ij} represents jth index for a sizing alternative in ith individual of population and $N^{\max}_{ST,j}$ denotes the maximum values of indices for sizing alternatives. The population of these individuals have been generated and inputted to the operational strategy problem for working out the operating strategy for the resources.

Calculation of fitness of population

After the generation of initial population, fitness for each individual for a particular function is evaluated. In the given problem, the objective function comprises of two parts – installation cost and operation cost as mentioned in eqs. (5.11-5.12). To evaluate the value of fitness function, the installation cost is first calculated using eq. (5.11). The optimal operational strategy is then determined and the total operation cost is being calculated using eq. (5.12). The total cost is then computed by adding the cost terms corresponding to eq. (5.11) and eq. (5.12).

Creation of offspring population

The next step is the creation of offspring population with the number of individualas as population size. After each solution is assigned fitness, it is mutated by using a zero-mean normally distributed probability distribution and a variance dependent on the fitness function to create the offspring population. The offspring population is generated using the following relation:

$$OP_{ij} = Round(IP_{ij} + Norm(0, \sigma_j^2)) \tag{5.42}$$

where, OP_{ij} represents value of jth variable corresponding to ith individual of the offspring population. IP_{ij} represents value of jth variable corresponding to ith individual of the existing population. $Norm(0, \sigma_j^2)$ is the normally distributed random number with mean value of 0 and standard deviation of σ_j which can be calculated as:

$$\sigma_j = (y_j)\left\{ \frac{F_i^{Fit} - F_{\min}^{Fit}}{F_{\max}^{Fit} - F_{\min}^{Fit}} + e^r \right\} \tag{5.43}$$

where,

$$y_j = \begin{cases} N^{\max}_{ST,j} & j = 1 \, to \, ST_{AV} \\ N^{\max}_{BT,(j-ST_{AV})} & j = 1 + ST_{AV} \, to \, BT_{AV} + ST_{AV} \\ N^{\max}_{EM(j-ST_{AV}-BT_{AV}-ET_{AV}-SE_{AV}-WE_{AV}-ME_{AV}-WM_{AV}-BM_{AV}-TM_{AV})} & \begin{aligned} j = {} & ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} + WE_{AV} + \\ & ME_{AV} + WM_{AV} + BM_{AV} + TM_{AV} \\ & + 1 \, to \, ST_{AV} + BT_{AV} + ET_{AV} + SE_{AV} \\ & + WE_{AV} + ME_{AV} + WM_{AV} + \\ & BM_{AV} + TM_{AV} + EM_{AV} \end{aligned} \end{cases}$$

(5.44)

where, $F^{Fit}_{\max}$ and $F^{Fit}_{\min}$ are the maximum and minimum values of fitness function for the existing population; e represents a positive number slightly less than unity and r represents the iteration counter. The fitness values are calculated for each individual of offspring population.

Competition and Selection

After the mutation operation, both parent and offspring populations are combined together and the best N solutions are probabilistically selected for the next generation. A score is obtained by competing the randomly selected opponents. The score m_i for the i^{th} individual is calculated as:

$$m_i = \sum_{k=1}^{N^i_{tour}} \varepsilon_K \tag{5.45}$$

where, $$\varepsilon_k = \begin{cases} 1 \, if F^{Fit}_i > F^{Fit}_k \\ 0 \quad otherwise \end{cases} \tag{5.46}$$

where N^i_{tour} is the number of tournaments faced by the i^{th} individual and is chosen randomly. After competition, different individuals from initial and offspring populations are sorted in the descending order of their scores and the high performers, equal in count to the population size, are selected as parents for the next generation. This completes one iteration/generation of the proposed EP based technique.

Stopping criterion

At the end of each iteration, the difference between minimum and maximum fitness values of parent population is calculated. If the difference is found to be less than a pre-specified tolerance (equal to zero in the present case), then the algorithm is terminated; otherwise steps 3 to 5 are repeated.

The main stages of the proposed hybrid technique including initialization, mutation and competition are illustrated with the help of a flowchart in Fig.5.1.

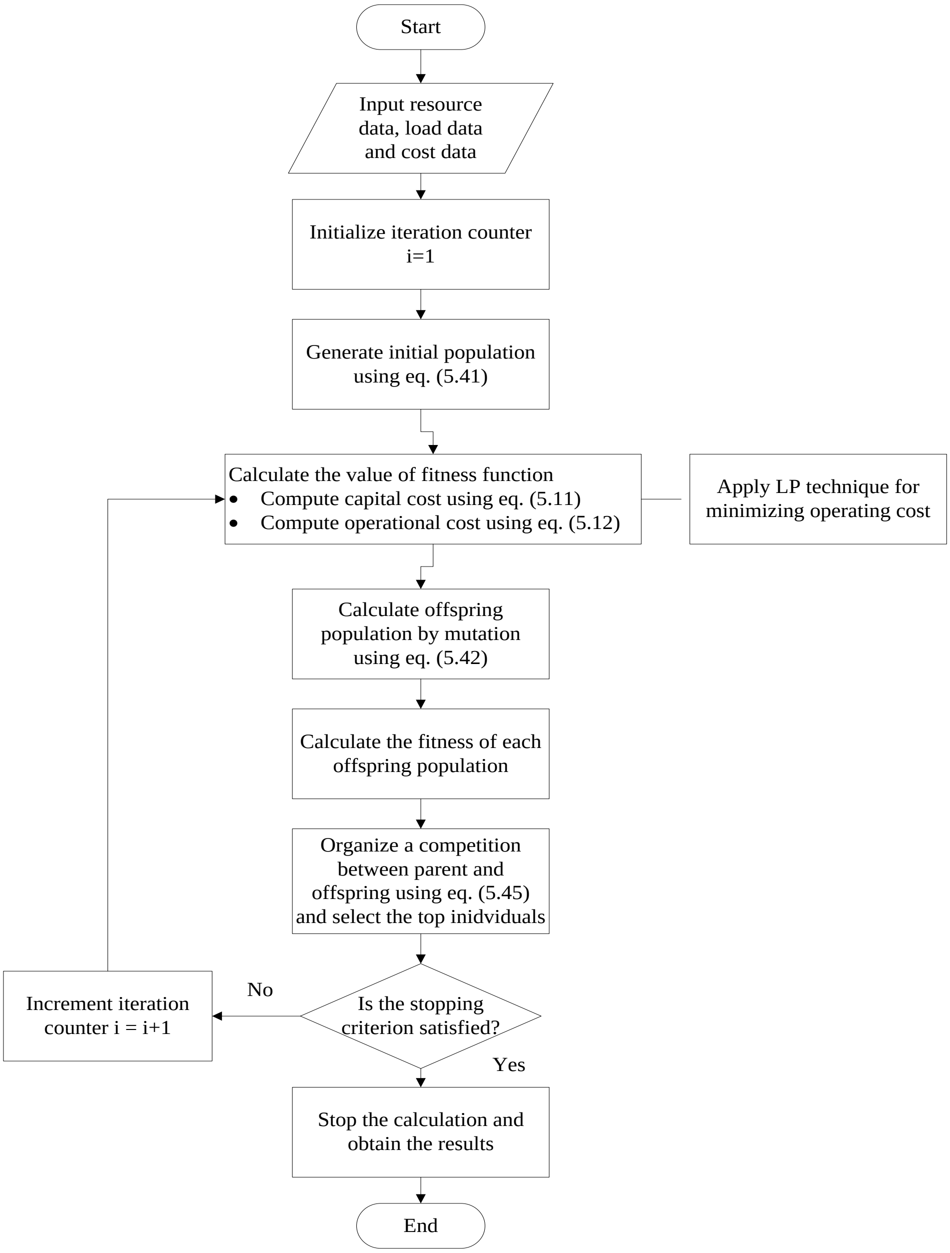


Fig. 5.1: Flowchart for the proposed technique

5.4 RESULTS AND DISCUSSION

A generalized system has been considered for the problem formulation. The formulated problem is applied for the site data as discussed in Chapter 2. The different alternatives for energy generation with their cost considered in the study are presented in Table 5.1.

Table 5.1: Different energy conversion facilities along with their cost

Energy Conversion Facilities	Type	Size (kW)	Cost in INR
Solar –Thermal	A	3	5000
	B	6	7000
	C	8	12000
Biomass - Thermal	A	2	16200
	B	4	27800
	C	6	48900
Biomass – Mechanical	A	2	38000
	B	5	93000
Wind- Electrical	A	3	80000
	B	6	210000
	C	9	450000
Wind -Mechanical	A	2	45000
	B	4	105000
	C	6	195000
Solar-Electrical	A	3	210000
	B	4	290000
	C	6	550000
Electrical – Thermal	A	1	2000

Contd……

Energy Conversion Facilities	**Type**	**Size (kW)**	**Cost in INR**
	B	2	3500
	C	3	4500
Electrical-Mechanical	A	2	15000
	B	4	32000
	C	6	55000
Mechanical – Electrical	A	10	75000
	B	15	122000
Thermal - Mechanical	A	2	38000
	B	4	82000

The coding for the formulation has been done in MATLAB and the program has been run for the mentioned data. Sizing problem, defined in Eqs. (5.11) and (5.31)-(5.40), is first solved through EP an a population of discrete sizes have been generated. With these sizes, scheduling problem, defined in Eqs. (5.12) and (5.14-5.30) is solved and the value of fitness function is obtained. The program is run till the stopping criteria are met. The values of different variables as obtained from program are given in Table 5.2.

Table 5.2: Optimal configuration of variables

Solar-Thermal	$N_{ST,1}$	0
	$N_{ST,2}$	1
	$N_{ST,3}$	0
Biomass- Thermal	$N_{BT,1}$	1
	$N_{BT,2}$	0
	$N_{BT,3}$	0
Biomass-Mechanical	$N_{BM,1}$	1
	$N_{BM,2}$	0
Wind-Electrical	$N_{WE,1}$	0
	$N_{WE,2}$	0
	$N_{WE,3}$	1
Wind-Mechanical	$N_{WM,1}$	1
	$N_{WM,2}$	0
	$N_{WM,3}$	0
Solar-Electrical	$N_{SE,1}$	0
	$N_{SE,2}$	1
	$N_{SE,3}$	0
Electrical – Thermal	$N_{ET,1}$	0
	$N_{ET,2}$	0
	$N_{ET,3}$	0
Electrical-Mechanical	$N_{EM,1}$	1
	$N_{EM,2}$	0
	$N_{EM,3}$	0
Mechanical – Electrical	$N_{ME,1}$	0
	$N_{ME,2}$	1
Thermal - Mechanical	$N_{TM,1}$	0
	$N_{TM,2}$	0

The total cost of the system comes out to be Rs. 1,075,324.00. For a typical day, if the mechanical-electrical energy conversion facility is not available then with the available discrete sizes presented in Table 5.1, there will be a deficit of electrical power as shown in Fig. 5.2.

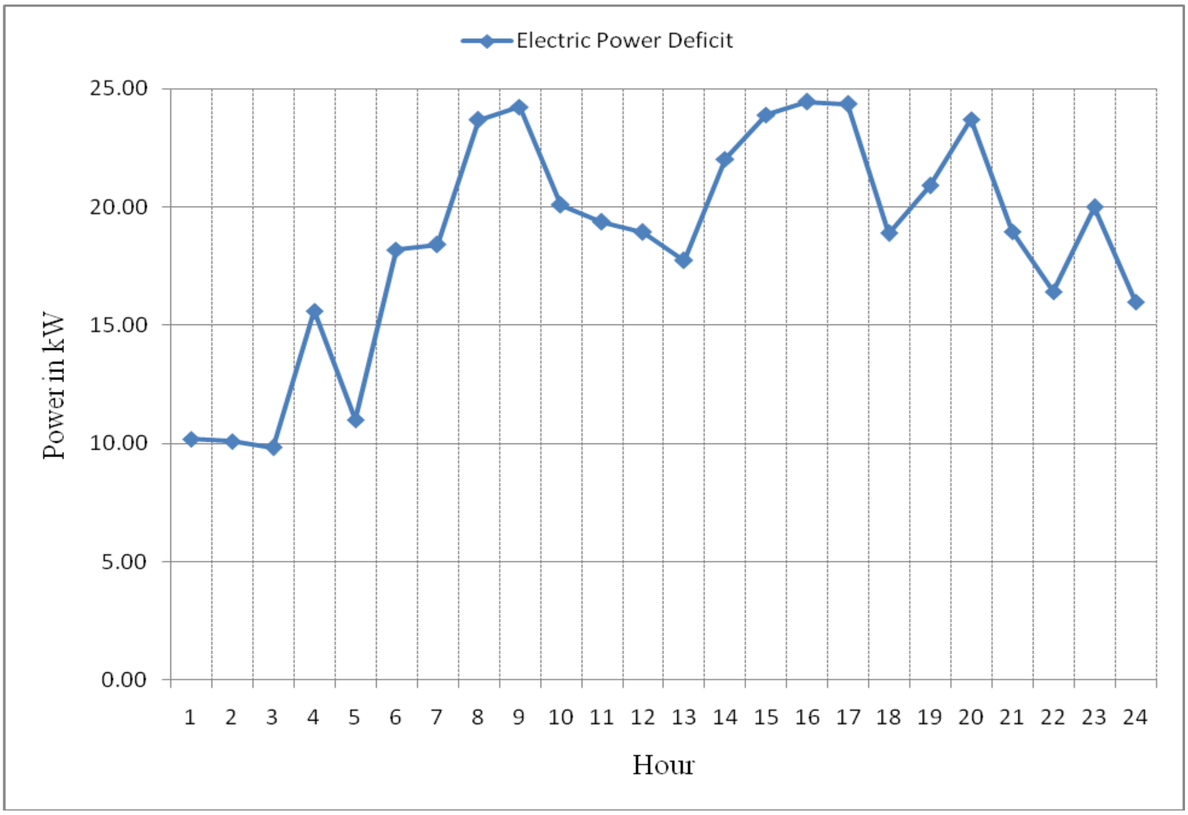


Fig. 5.2: Variation of electric power deficit without the availability of conversion facility

The absence of a conversion facility leads to a deficit of electric power.This also leads to deficit of power required for electrical-thermal facility and electrical to mechanical facility as shown in Fig. 5.3

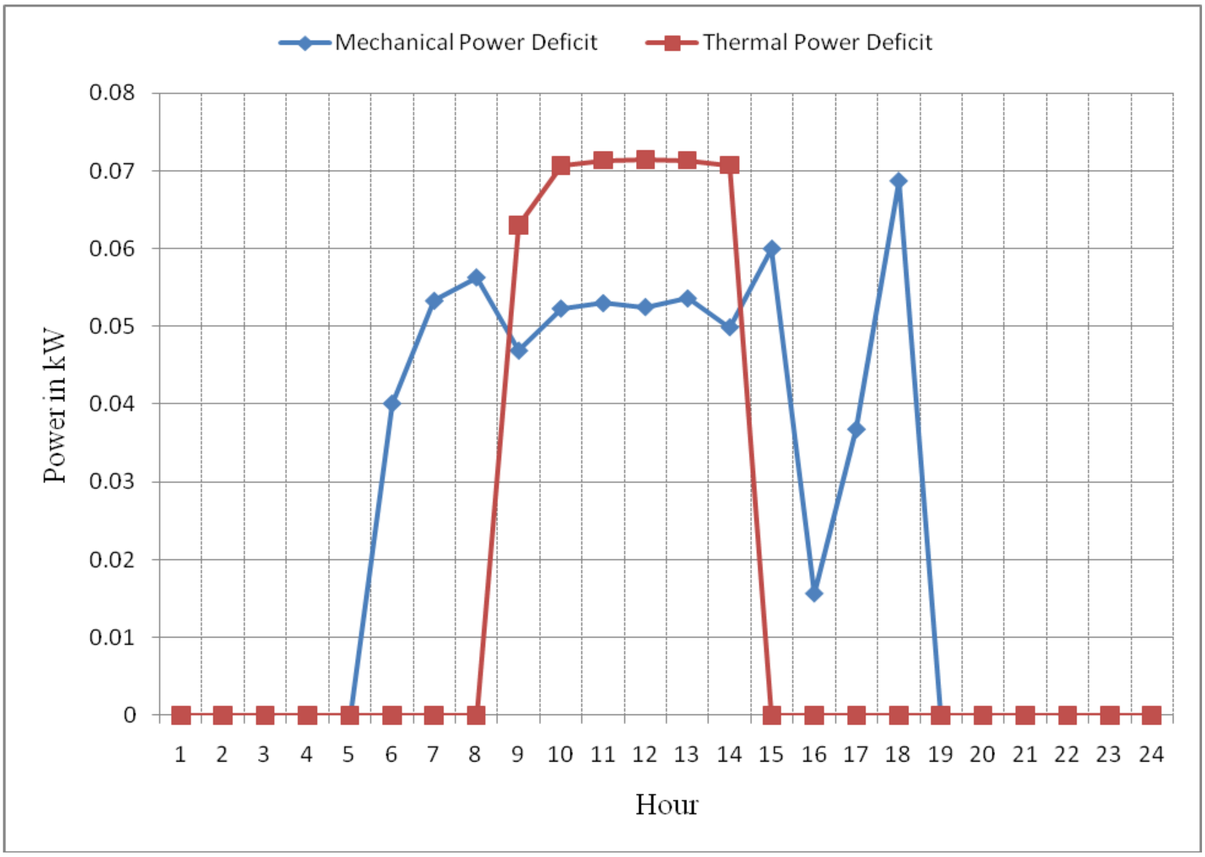


Fig. 5.3: Variation of mechanical and thermal power deficit

This deficit can be compensated either through the availability of facility or through increasing the sizes of the solar or wind energy generator.

5.5 CONCLUSION

The following points can be summarized from the above discussion:

- An optimal planning of integrated renewable energy system has been done in this study. The optimal sizes for different energy conversion facilities along with their operational strategy have been worked out in this chapter.
- An objective function of total cost inclusive of capital and operation cost has been considered and a hybrid EP-LP technique has been applied for

optimization. The sizes considered were discrete, hence the sizing problem has been solved through evolutionary programming technique.

- The results as the values of different variables which implied the number of energy conversion facilities of a size has been obtained along with the total cost of the system.

CHAPTER-6

CONCLUSIONS

6.1 GENERAL

Utilization of renewable energy resources in an integrated manner is a good option where it is infeasible to supply through grid. The scope of integrated energy system as a source of energy for a remote rural area has been investigated. It was presented through a rigorous literature survey that a system comprising of the locally available renewable energy resources can resolve the energy issues and suffice for the different energy demands of a remote site. This chapter presents the main conclusions derived from the present study.

6.2 CONCLUSIONS

A remote rural site has been selected considering the various factors for the selection of the site. It was found that the selected site has an ample potential of solar, wind and biomass energy resources. Based on the site data available, an integrated system comprising solar/wind /biomass has been proposed. The demands of the site have also been studied.

In order to plan the operation of the integrated renewable energy system, it is necessary to obtain the hourly data of different resources. In this context, a day-ahead scenario has been presented by predicting the different resources through an artificial network based technique. The operational strategy has been worked out for different energy conversion facilities to supply different energy demands at minimum operation cost.

A sizing methodology has been described to work out the different sizes of the energy conversion facilities. The sizing has been optimized such that the overall cost including capital and operational cost comes out to be minimum.

Main findings and conclusions of the present study are drawn as given below:

i. IRES is a good option for supplying energy demands of a rural remote site. In this study, a remote village of Kinnaur district of Himachal Pradesh has been considered.

ii. Based on the data collected, it has been found that there is a good potential of solar, wind and biomass energy resources. The annual solar radiation at the site is found to be 1689.95 kWh/m^2. The average wind speed at the site is found to be 5m/s. The amount of biomass available is sufficient to produce 164m^3 of biogas per day.

iii. The total demands of the site are classified as – thermal, electrical and mechanical. The domestic electrical energy requirements are found to be 152562 kWh/yr. The other electrical energy requirements are found to be 17702kWh/yr. In order to study the load profile, the entire year has been divided as Dec-Feb as season – I, Mar – May as season – II, Jun – Aug as season – III and Sep – Nov as season – IV. Season wise peak load has been estimated as 42.25 kW for season –I, 47.24 kW for season –II, 30.24 kW for season – III and 44.98 kW for season – IV.

iv. In order to utilize renewable energy resources, IRES has been developed with different energy conversion facilities. The energy conversion facilities considered in this study are: solar – thermal, biomass – thermal, electrical – thermal, solar – electrical, wind – electrical, mechanical – electrical, wind – mechanical, biomass – mechanical, thermal – mechanical and electrical – mechanical energy conversion facility. The modeling of these facilities has been done in order to evaluate the power output from different energy conversion facilities.

v. The modeling of solar and wind energy resources has been done in a day-ahead scenario using artificial neural network. The regression coefficient values of solar radiations for season I-IV are 0.93, 0.96, 0.96 and 0.93 respectively. Similarly, the regression coefficient values of wind speeds for season I-IV are 0.88, 0.84, 0.98 and 0.86 respectively.

vi. With these conversion facilities, an operational strategy has been worked out. An optimization problem has been formulated with the objective function of the cost of operation of different energy conversion facilities and the cost of energy not served. The linear programming optimization problem with 266 variables, 23 equality constraints and 52 inequality constraints has been solved through Optimization Toolbox of MATLAB. The operational strategy for a typical day has been obtained different factors (α_{TL})ratio of thermal energy not served to the total thermal load, (α_{EL}) ratio of electrical energy not served to the total electrical load and (α_{ML}) ratio of mechanical energy not served to total mechanical load are included to check the energy not served for different demands. It was found that value of 0.56kWh of thermal energy gets unserved and 0.63kWh of electrical energy remains unserved for a typical day.

vii. For optimal planning, the overall cost of the system should be minimum. Hence, the overall cost has been considered in objective function which comprises of capital as well as operational cost. The capital cost is governed by the size of energy conversion facility, while the operation cost is governed by power output at different instant of time.

viii. Hence, the developed formation has both the discrete as well as continuous variables. A hybrid EP-LP based approach under MATLAB environment has been proposed to solve the developed formation. A discrete size selection has been made through evolutionary programming (EP) and with the help of these sizes, the operational strategy has been worked out with minimum operational cost using linear programming technique. The fitness function has been evaluated by combining operational cost and capital cost.

ix. The sizes for different energy conversion facilities have been obtained as- solar thermal energy conversion facility of 6kW, biomass-thermal facility of 2kW, biomass-mechanical facility of 2kW, wind-electrical of 9kW, wind –mechanical of 2kW, solar-electrical of 4kW, electrical –mechanical of 2kW and mechanical-electrical of 15kW. The total cost of the system is found to be Rs. 1,075,324.00.

Hence, these integrated energy systems are the most suitable sources of energy for all kinds of rural demands whether it be thermal energy demand for cooking, mechanical energy demand for water pumping and electrical energy demand for various applications.

6.3 FUTURE SCOPE

The voids left in the current research work led to the evolution of future research work. The current work emphasizes on the utilization of integrated renewable energy systems with solar, wind and biomass as energy resources leaving as scope for addition of other resources. Future research should include other renewable energy resources like hydro-power resources in the studied model. Besides the resources, there is a need for reliability analysis with the inclusion of some storage devices as well as dump load. There is a scope of realization of proposed operational strategy by designing an adaptive controller.

APPENDIX-A

EVOLUTIONARY PROGRAMMING

A concise overview of Evolutionary Algorithms (EAs) has been deliberated in this Appendix, henceforth the Evolutionary Programming (EP) method has been elaborated. These are the (EAs) artificial intelligence approaches, which follow the natural evolutionary convention to compose search and optimization issue. EAs have drawn more attention in resolving dissimilar optimization problems because of their strength to discover global optima conveniently with a quick and powerful convergence ratio, despite the exhausting and complex nature of problems. EAs may have subsequent merits over the conventional classical optimization methods (Dev, 2002; Lee and Yang, 1998; Wu and Ma, 1995; Yuryevich and Wong, 1995):

1. EAs employ multiple point search rather single point search, by that determining additional hills and valleys, and lowering the possibility of attaining the local optima,

2. EAs apply payoff (fitness) functions precisely to find direction and do not need derivatives or any more supplementary information. Consequently, EAs can handle non-smooth, non-continuous, and non-differentiable functions conveniently,

3. Unlike the traditional optimization methods, EAs do not need any kind of approximation in solving the optimization problems,

4. To find out the global optima EAs utilize the principle of probabilistic evolution rules to preferable generations rather than deterministic rules, and therefore, can

explore a complex and erratic field to discover the global optima,

5. EAs have built-in computational competence to compute all distinctive in the population which is autonomous to rest,

6. Additionally, EAs are very extensible and strong enough than traditional optimization techniques.

The EAs are basically used the procedure of natural selection such as: mutation, recombination, reproduction, selection, etc. Mutation anyhow confound a candidate solution; aggregate randomly joins their components so that it can be yield to a unique solution; reproduction imitate the best optimal solution initiated in a population; and selection evacuates the indigent solutions within a population. EAs give a leading generations along with candidates, which are subsequently superior and easily adapted to their domain in the beginning of primary generation of candidate solutions (Lee and Yang, 1998).

Few examples of EP are EAs like Genetic Algorithm, Evolutionary Strategy, etc. EP algorithms practice of vectors, comprising of a described number of solutions. The solution vector is generally named as population; while number of solutions in a population terms as population size; and each solution in a population is indicated as an individual, which encompasses the attributes of various variables of the problem to be solved. To solve an optimization problem using EP algorithm different computational steps are involved and may elaborate as follows:

Step I. Initialization

An EP algorithm is begun by creating a population of individuals and all variables of an individual are elected in either way from a homogeneous random number allocated within its possible extent.

Such as, if any variable j is confined by its lowest value and highest value, then variable can be initialized by using following equations:

$$IP_{ij} = x_j^{Min} + U_{(0,1)} \cdot \left(x_j^{Max} - x_j^{Min} \right) \tag{A.1}$$

where,

IP_{ij} = j^{th} variable in i^{th} individual of the initial population,

x_j^{Min} = Minimum value of j^{th} variable,

x_j^{Max} = Maximum value of j^{th} variable,

$U_{(0,1)}$ = A uniformly dispersed random number between 0 and 1.

Step II. Computation of fitness for Initial population

In this step, the value of fitness function is estimated for every individual of the original population, as achieved in step I. The fitness function express the coveted objective function. Occasionally, the penalty terms, follow the constraints, are also include in the objective function so as to evolve the fitness function.

Step III. Formation of offspring population

The offspring population of the solutions is conceived from the actual population over a mutation operator. Mutation operator randomly agitates a candidate solution by enumerating a commonly distributed noise. The degree of enforce random perturbation on each variable of an individual rely upon on the correlated fitness of individual. It can be expressed mathematically as:

$$OP_{ij} = IP_{ij} + NORM\left(0, \sigma_{ij}^2\right) \tag{A.2}$$

where,

OP_{ij} = j^{th} variable in i^{th} individual of the offspring population,

$NORM\left(0, \sigma_{ij}^2\right)$ = A normally distributed random number with a mean value of zero and a standard deviation of σ_{ij}.

The value of σ_{ij} can be estimated as:

$$\sigma_{ij} = \left(x_j^{Max} - x_j^{Min}\right)\left\{\frac{f_i - f^{Min}}{f^{Max} - f^{Min}} + a^r\right\} \tag{A.3}$$

where,

f_i = Value of fitness function corresponding to i^{th} individual of the existing population,

f^{Min} = Minimum value of fitness function within the existing population,

f^{Max} = Maximum value of fitness function within the existing population,

a = Positive number marginally less than unity,

r = Iteration number.

Step IV. Competition and selection

After creating the offspring population, the fitness is estimated for every individual within the offspring population in an identical way as explained in step II. The next step in an EP based approach is the competition step. A new population is generated in this step, from two existing (initial and offspring) populations using tournament scheme. Using this scheme, every individual within original population along with offspring population go through a sequence of tournament with randomly elected competitor and achieve a grade. The grade of an individual is estimated as:

$$s_i = \sum_{j=1}^{N_{Tour}} \alpha_j \tag{A.4}$$

where,

s_i = Grade for i^{th} individual,

N_{Tour} = Number of tournaments confront by an individual,

The value of α_j is given as:

$$\alpha_j = \begin{cases} 1 & \text{if } f_i < f_k \\ 0 & \text{otherwise} \end{cases} \tag{A.5}$$

where,

f_k = Fitness value for k^{th} individual, which is chosen randomly from initial and offspring populations,

After competition, the various individuals from initial and offspring populations are organize as par the decreasing manner with respect to their grades and finest individuals, alike to population size in count, are chosen as parent for the later generation as well as their fitness values. This conclude one iteration of an EP based approach.

Step V. Checking the stopping criterion

In the last of every iteration, the dissimilarity between lowest and highest values of parent population is estimated. If the dissimilarity is observed to be minor than a pre-specified tolerance, then the algorithm stops, otherwise, steps III to V are imitated. EP algorithm can also be stopped when the optimal solution is not apparently enhanced or the number of iterations surpass over a pre-described value.

The main steps of an EP based technique are outlined in flowchart in Fig. A.1.

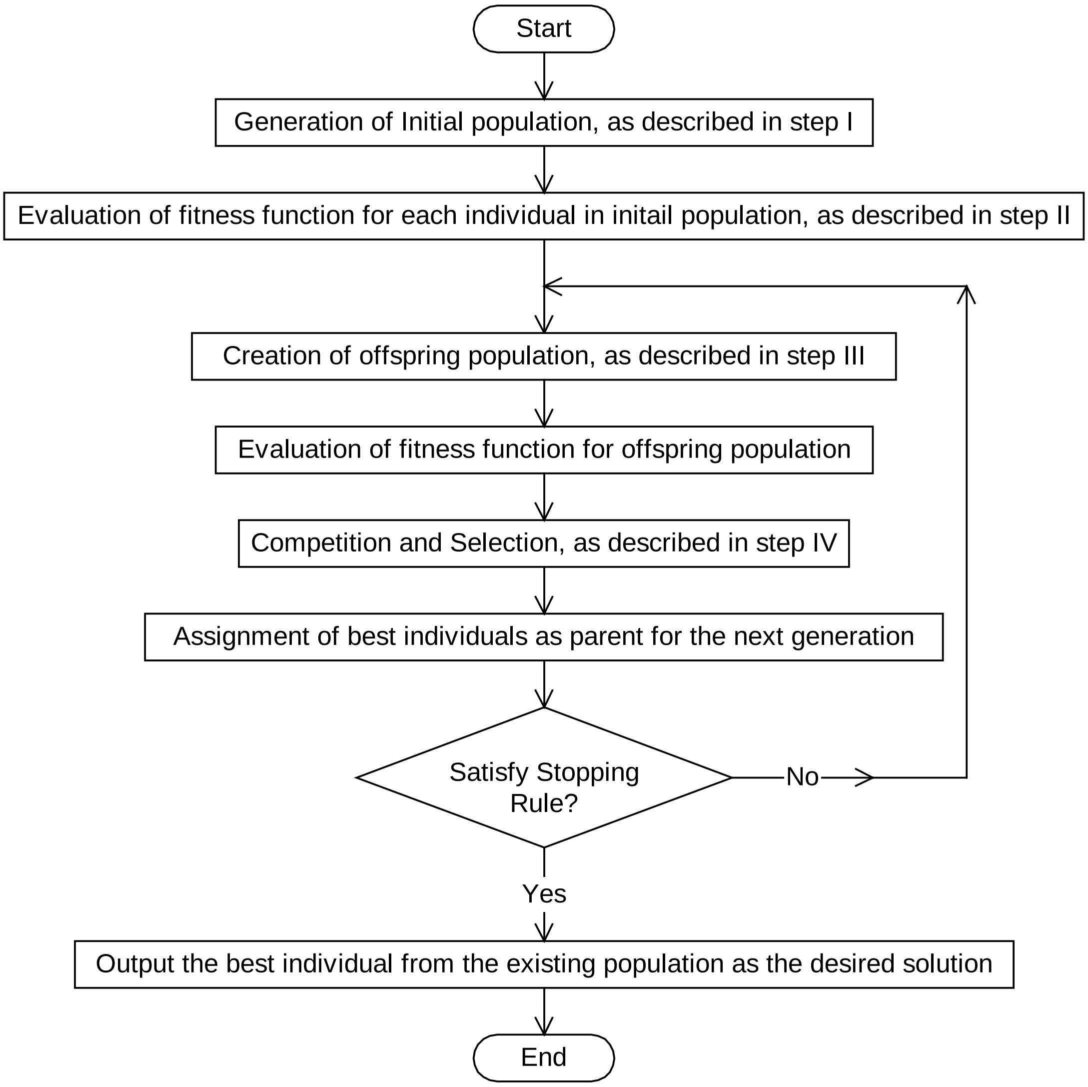


Fig. A.1: Illustration of an EP based algorithm

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CANDIDATE’S DECLARATION

I hereby certify that the work, which is being presented in the thesis entitled “**OPTIMAL PLANNING OF INTEGRATED RENEWABLE ENERGY SYSTEMS**” in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy and submitted in the Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from July, 2010 to November, 2014 under the supervision of Dr. R. P. Saini, Associate Professor, Alternate Hydro Energy Centre and Dr. D. K. Khatod, Assistant Professor, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee. The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

(MOHIT BANSAL)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(R. P. Saini)	(D. K. Khatod)
Supervisor	Supervisor

Date: November , 2014

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Journals

1. M. Bansal, R.P. Saini and D.K. Khatod, “Development of cooking sector in rural areas in India - A review”, Renewable and Sustainable Energy Reviews, Elsevier, Vol. 17, pp. 44-53, 2013.
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