Distributed Hybrid Renewable Polygeneration for Indian Villages: Optimization Studies

Thesis Submitted by

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2018

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INDEX NO. 226/13/E

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Book Chapters

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2. **Ray A**, De S, Distributed Polygeneration Using Solar Energy: A Future Sustainable Energy System for India; Applications of Solar Energy (Springer) 2018.doi 10.1007/978-981-10-7206-2_2

International Journal

1. **Ray A**, De S. Techno-economic optimization of a small scale distributed polygeneration with local resources for a remote place of India. **International Journal of Ambient Energy (Taylor and Francis)** doi. 10.1080/01430750.2019.1583129 ***(Accepted)***
2. **Ray A**, Jana K, Assadi M, De S, Distributed polygeneration using local resources for an Indian village: multi-objective optimization using metaheuristic algorithm. **Clean Technologies and Environmental Policy (Springer)** 2018. doi. 10.1007/s41660-018-0053-2 ***(Accepted)***.

3. **Ray A**, De S. Polygeneration using renewable resources: Cost optimization using linear programming. **Process Integration and Optimization for Sustainability (Springer)** 2018. doi. 10.1007/s41660-018-0053-2 ***(Accepted)***..
4. Jana K, **Ray A**, Majoumerd MM, Assadi M, De S. Polygeneration as a future sustainable energy solution- A comprehensive review. **Applied Energy (Elseivier)** 2017, 202, 88-111
5. **Ray A**, Jana K, De S. Polygeneration for an off-grid Indian village: Optimization by economic and reliability analysis. **Applied Thermal Engineering (Elseivier)** 2017, 116, 182-196.

4. List of Patents: Nil

5. List of Presentations in National / International / Conferences/Workshops/Symposiums:

1. **Ray A**, De S, Optimum design of a renewable based polygeneration using Flower Pollination Algorithm,International Conference in Mechanical Engineering (INCOM 18), 4-6 January 2018, Kolkata, India.
2. **Ray A**, Assadi M, De S, Cost Optimization of a Polygeneration using Renewable Resources, 6th International Conference on. Advances in Energy Research 2017(ICAER 2017), December 12–14, 2017, Mumbai, India.
3. **RayA** , Jana K, De S,Assadi M, Optimum design of pv-wind-biomass-fuel cell based polygeneration systemby using meta heuristic algorithm, Proceedings of the International Conference on Sustainable Energy and Environmental Challenges (SEEC-2017), 26 – 28 February, 2017, Mohali, India.
4. **Ray A,** Jana K, De S.Optimum energy solution of a remote off-grid village with polygeneration using local resources. International Conference on Renewable Energy Extension and Outreach (REEO 2016) at Viswa Bharati, Santiniketan, 20-21st March, 2016, India.

Certificate from the Supervisor

This is to certify that the thesis entitled **"Distributed Hybrid Renewable Polygeneration for Indian Villages: Optimization Studies"** submitted by Shri. Avishek Ray, who got his name registered on 24th October,2013 for the award of Ph.D (Engg.) degree of Jadavpur University is absolutely based upon his own work under the supervision of Dr Sudipta De and that neither his thesis nor any part of the thesis has been submitted for any degree or any other academic award anywhere before.

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I declare that the work described in this thesis is entirely my own. No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute. Any help or source information, which has been availed in the thesis, has been duly acknowledged.

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(Avishek Ray)

Dedicated to

My Parents

Acknowledgements

Research has been defined as the systematized effort to gain new knowledge. This journey to new insights becomes easier when one receives proper direction and encouragement. During my journey of PhD work, there were many ups and downs. I would like to express my sincere gratitude to those people who helped me to overcome all the hurdles throughout my PhD period.

First and foremost, I would like to gratefully acknowledge my PhD supervisor, Prof. Sudipta De. It is not an exaggeration to say that my curiosity and eagerness in research was evoked byProf. Sudipta De. I would like to thank him for inspiring me to pursue excellence. The discussions with him stimulated to explore new ideas. The importance of supervision is well-known to anyone who conducts research. In this context, I would thank my supervisor for his unconditional support.

I will also like to thank Dr.Kuntal Jana, who has been absolutely kind hearted and never refused my request for any kind of help. His research ideas and motivations helped me to shape my research.

Next, I want to express gratitude to my parents for standing by me always and keeping faith on me. It can’t be expressed in words what my parents did for me and still doing for me. I must thank my parents for helping me in every step of my life and pampering me so much.

Next, I like to thank my wife Dr Poulami Das for helping me always and holding my hands during my hard times. I also like to express my lab mates specially Mr Joydeep Datta , Mr Sujit Saha and Mr Soumitra Pati for continuous support. I like to thank Mr Binoy Sukla and all other staff of Heat Power Laboratory of Mechanical Engineering Department, Jadavpur University for their help and continuous support.

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Abstract

Presently, primary sources of energy are mostly fossil fuels. These fossil fuels have the serious limitation of Green House Gas emission.

Efforts are made to design the carbon free energy systems. Distributed polygeneration is an option for using local resources to cater to the needs of local people. It is an integrated system with multiple outputs from a single unit for better performance. In this study the optimization of a multi-input and multi-output polygeneration is carried out using linear and metaheuristic algorithms.

Objective of this present work is to design a multi-input and multi output system with proper capacity determination of the components for best economic and technical performance.

In this thesis, linear programming and metaheuristic approaches are carried out to determine the optimized capacities of the individual components. The comparative study shows that the metauheuristic approach is better than other approaches in terms computational efficiency. The cuckoo search algorithm is compared with other metaheuristic algorithms like genetic algorithm, particle swarm optimization etc and the solution is found to be better. The quantum inspired cuckoo search algorithm proves better than the cuckoo search technique. The integrated energy systems are designed for catering the local people. The systems are designed to ensure 100% reliability of power supply. Other utilities like ethanol, potable water and rich calorific value gas are also generated.

Results of this study show that the increase in the reliability of power supply lowers levelized cost of electricity which is a socially acceptable solution. Proper resource utilization by hybridization is also important issue. In this study both the single objective and multi-objective optimization is carried out. The optimization is carried out for economy, environmental and socio-economic factors like land requirement etc. The levelized cost of electricity is found out to be competitive with the grid power.

Title of the Thesis

Distributed Hybrid Renewable Polygeneration for Indian Villages: Optimization Studies

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Symbols and Abbreviations

Abbreviations

AC	Annualized cost, INR/year
AE	Annualized expenditure, INR/year
AI	Annualized investment, USD
AL	Agricultural load, kW
AP	Annualized profit, INR/year
AR	Annualized Revenue, INR/year
AS	Annualized savings, (INR/year)
BG	Biomass Gasifier
COP	Co-efficient of Performance
CRF	Capital recovery factor
CSA	Cuckoo Search Algorithm
CV	Calorific Value, kJ/kg
DG	Distributed generation
DL	Domestic load, kW
FC	Fuel cell
GA	Genetic Algorithm
GoI	Government of India
H	Hydrogen
LCOE	Levelized Cost of Electricity, USD/kWh
LPSP	Loss of Power Supply Probability, %
MaxIteration	Maximum iteration
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
OP	Optimized profit, INR/year
PEM	Proton Exchange Membrane
PSO	Particle Swarm Optimization
PV	Photovoltaic
QICSA	Quantum Inspired Cuckoo Search Algorithm
Rand	Random variable
RGGVY	Rajiv Gandhi Grameen ViduytikaranYojna
T_A	Agricultural load, kW
T_D	Domestic load, kW
T_L	Total load, kW
T_s	Street light load, kW
TVC	Thermal Vapor Compression
UL	Unmet load
VAM	Vapor Absorption Machine
WT	Wind turbine

Symbols

$\dot{S}_h$	Feed rate of straw, kg/h
$C_{PV_{module}}$	Annualized cost of solar module, INR/year
C_{eqb}	Cost of bio gas system of capacity b, USD
C_{ethy}	Annualized catalyst requirement, kg/year
C_{pv}	Total Cost of PV module, INR
$C_{pvperkw}$	Cost of PV module per kW, INR/kW
CV_{biogas}	Calorific value of biogas, MJ/m^3
$C_{windperkw}$	Cost of wind turbine per kW, INR
E_{bio}	CO_2 emission of biomass gasifier per kWh electricity produced, g
E_{ge}	Electrical power output of the gas engine, kW
El_{bio}	Total units of electricity generated by the biomass gasifier per year, kWh
El_{solar}	Total units of electricity generated by the PV module per year, kWh

E_{RR}	Percentage of emission of CO2 reduction per year
E_{solar}	CO2 emission by solar module per kWh electricity produced, g
Eth_{kg}	Ethanol yield per kg of catalyst, liters/year
Eth_{y}	Ethanol yield per year, liters/year
F_{g}	Amount of flue gas generated per kWh of electricity, kg
F_{sp}	Specific heat of flue gas, kCal/kg
H_{vam}	Heat required to runvapour absorption chiller, kW
η_{G}	Electrical conversion efficiency of gasifier-gas engine set, %
η_{c}	Efficiency of combustion, %
$PV_{installed}$	Installed capacity of PV module, INR
TC_{esep}	Total initial cost of the ethanol separation unit, INR
TC_{esyn}	Total initial cost of the ethanol synthesis unit, INR
$VAM_{\mathbf{cap}}$	Capacity of vapor absorption chiller, kW
$VAM_{\mathbf{cop}}$	Coefficient of performance of vapor absorption chiller, kW
$Wind_{installed}$	Capacity of wind turbine, kW
C_{D}	Yearly cost of cattle dung, INR/year
C_{Dperkg}	Cost of dung per kg, INR/kg
C_{R}	Yearly revenue earned from selling cooling utility, INR/year
C_{eqa}	Total Cost of biomass gasifier of capacity a, INR
C_{eqb}	Total Cost of biomass gasifier of capacity b, INR
C_{etss}	Total cost of ethanol separation unit, INR
C_{etsy}	Total cost of ethanol synthesis unit, INR
C_{straw}	Annual cost of straw, INR/kg
$C_{strawperkg}$	Cost of straw per kg, INR/kg
D_{a}	Availability of dung per day, kg
E_{syn}	Total cost of ethanol synthesized, liters
Eth_{R}	Yearly revenue earned from ethanol selling, INR/year
$P_{bio}(k)$	Biomass at kth instant, kW
$P_{solar}(k)$	Power output of solar module at kthinstant , kW
W_{R}	Yearly revenue earned from selling potable water, INR/year
θ_{z}	Zenith angle, degrees
AL	Agricultural load, kW
BG_{avail}	Availability of biogas per day, m^{3}/day
CAGR	Cumulative annual growth rate, %
C_{BG}	Annualized cost of gasifier, INR/year
C_{ckg}	Cost of catalyst per kg, INR/kg
C_{eqa}	Cost of biogas system capacity a , USD
C_{ethsep}	Annualized cost of ethanol separation, INR/year
C_{ethsyn}	Annualized cost of ethanol synthesis, INR/year
CE_{total}	Total initial cost of the electrolyzer, USD
CF	Annualized fuel cost, USD/year
$CFC_{installed}$	Total installed capacity of the fuel cell system, kW
CFC_{total}	The total cost of fuel cell installation, USD
C_{g}	Cost of gaseous mixture, USD/kg
C_{GE}	Annualized cost of gas engine, INR/year
C_{ge}	Annualized cost of gas engine, INR/year
CH_{kg}	Cost incurred to transport 1 kg of hydrogen, USD
CH_{s}	Cost of hydrogen storage, USD
C_{inv}	Cost of inverter, USD/watt-peak
CM	Annualized maintenance cost, USD/year
C_{MoS2}	Annualized cost of MoS_{2} catalyst, INR/year
COP	Coefficient of performance
C_{p}	Revenue from cooling, INR/year
C_{p}	Betz limit

CP_{elec}	Cost of electrolyzer per watt, CHF
CP_{fc}	Cost of fuel cell per watt, USD
CP_{sol}	Cost of PV module per watt, USD
CP_{total}	Total cost of PV module, USD
C_r	Revenue from cooling utility, INR/kW
CRF	Capital recovery factor
C_{straw}	Annualized cost of straw, INR/year
C_{vam}	Annualized cost of vapor absorption cooling system, INR/year
CV_{bio}	Calorific value of biogas, kJ/m^3
CV_g	Calorific value of the gaseous mixture, kJ/kg
CV_h	Calorific value of hydrogen, kJ/kg
CV_s	Calorific value of straw, MJ/kg
CV_{straw}	Gross calorific value of straw, kJ/kg
CV_{wood}	Gross calorific value of wood, kJ/kg
C_{WH}	Annualized cost of waste heat recovery system, USD
C_{wind}	Total cost of wind turbine, INR
$CW_{inperkW}$	Cost of wind turbine per kW,USD
CW_{total}	Total initial investment for wind turbine installation, USD
C_y	Yearly requirement of catalyst, kg
D_a	Amount of dung fed to the digester, kg
DDG	Decentralized distributed generation
DG	Diesel generator set
DL	Domestic load, kW
E_D	Total electrical energy deficit per year, kWh
$E_{deficit}$	Yearly electrical energy deficit, kWh/year
E_{fc}	Electricity generated by the fuel cell, kW
E_{ge}	Electricity output of gas engine, kWh
E_L	Total electrical energy required per year, kWh
$EL_{installed}$	Installed capacity of electrolyzer, kW
E_R	Revenue from ethanol, INR/year
E_t	Total units of electricity generated in the life of the plant to cater the local load, kWh
E_{thc}	Ethanol produced per kg of catalyst
E_{thy}	Ethanol produced per year, litres
E_{year}	Electricity generated per year, kWh
FC_{ins}	Total installed capacity of the fuel cell system, kW
F_g	Emission factor of fuel cell,g-CO_2
F_g	Amount of flue gas generated per kWh of electricity, kg/kWh
F_{sp}	Specific heat of flue gases, k Cal/°C
G	Total GHG emission, g-CO_2
G_d	Emission factor of biogas digester,g-CO_2
GDP	Gross Domestic Product
G_g	Emission factor of biomass gasifier,g-CO_2
GHG	Greenhouse gas
G_s	Emission factor of solar module,g-CO_2
H	Hours
H_d	Maximum hydrogen required per day, kg
HDI	Human Development Index
$H_{elec}(t)$	Instantaneous amount of hydrogen produced, kg
H_{fc}	Amount of hydrogen fed to fuel cell, kg
H_{kg}	Cost incurred to store 1 kg of hydrogen in metal hydride tank , USD/kg
$H_{waterkg}$	Heat needed to produce 1kg of water, kW
H_y	Total amount of hydrogen transported per year, kg
I	Bank discount rate, %
I(t)	Instantaneous output current of solar module , Ampere
I_b	Total beam radiation on a surface, $Watt/m^2$
I_d	Total diffuse radiation on a surface, $Watt/m^2$

$I_{incident}$	Solar radiation falling on the module at time t, Watt/m^2
In_{cap}	Capacity of the solar inverter, kW
In_{pp}	Price per watt-peak of solar inverter, INR/watt-peak
INR	Indian Rupees
I_T	Total radiation on a tilted surface, Watt/m^2
I_t	Investment expenditure, INR/year
L(k)	Load at k^{th} instant, kW
L	Total land requirement, m^2
L_{bio}	Land requirement for 1kW of biogas installation, m^2
LCOE	Levelised cost of electricity, INR/kWh
LPSP	Loss of Power Supply Probability
L_{sol}	Land requirement for 1kW of PV installation, m^2
L_{wind}	Land requirement for 1kW of WT installation, m^2
M_c	Maintenance cost, INR/year
MNRE	Ministry of New and Renewable Energy
N	Economic life of the system, years
NF_G	Normalization factor for GHG emission
NF_L	Normalization factor for land requirement
NF_{LCOE}	Normalization factor for LCOE
NPV	Net Present Value
OP	Operating hours of gas engine per annum, hours
P_{bioh}	Least electricity output of the gas engine required to provide sufficient waste heat to WHRVAM, kW
$P_{biomass}$	Electricity output of gasifier, kW
PEC	Per capita Energy Consumption
P_{load}	Total electrical load in a year, kWh
Ppm	Parts per million
P_r	Reliability of power supply,%
$P_{sol}(t)$	Instantaneous output power of solar module , kilowatts
P_{solar}	Electricity output of solar PV module, kW
PV	Photovoltaic
PV (m)	Power output of solar module at 1000 W/m^2, kW
$PV_{installed}$	Installed capacity of PV module, kW
P_{wind}	Power generated by wind turbine at t^{th} instant, kW
$P_{wind}(k)$	Wind power at k^{th}instant,kW
R (i)	Radiation at the i^{th} instant, Watt/m^2
R(t)	Radiation at t^{th} instant, W/ m^2
r_b	Tilt factor for beam radiation
r_d	Tilt factor for diffuse radiation, Watt/m^2
R_G	Annualized revenue earned from hydrogen selling, USD
r_r	Tilt factor for reflected radiation, Watt/m^2
R_{WH}	Annualized revenue from waste heat,USD
R_y	Revenue earned per year, USD
S	Scale factor for biomass gasifier
S	Scale factor for costing of wet biogas systems
S_{cap}	Capacity of solar module, kW
SC_{perkg}	Cost of straw per kg, INR/kg
SD_{max}	Maximum straw demand, kT/year
S_e	Scale factor for ethanol synthesis
S_{in}	Straw input to gasifier, kg/hr
SL	Street light load, kW
S_{pv}	Cost of solar module per watt pear, INR/watt-peak
S_s	Scale factor for ethanol separation
T	Unit cost of electricity, INR/kWh
TC_{WHRVAM}	Total cost of Waste Heat Recovery Vapour Absorption Cooling System
$T_{failure}$	Yearly total power failure time, hr/year

t_g	Temperature at exit of turbo-generator, °C
TL	Total load, kW
T_{total}	Total hours of operation of the plant, hr
UL	Unmet Load probability
USD	United States Dollar
v(t)	Velocity of the wind, m/s
V(t)	Instantaneous voltage output of solar module, Volts
$W_{brackish}$	Brackish water fed to TVC unit, litres
W_f	Weighing factor for LCOE
W_G	Weighing factor for GHG emission
W_H	Waste heat generated by the gas engine, kW
WH_{ge}	Waste heat generated by the gas engine, k Cal/hr
WHRVAM	Waste heat recovery vapour absorption machine
$W_{installed}$	Total capacity of wind turbine, kW
W_L	Weighing factor for land requirement
W_p	Watt-peak
$W_{potable}$	Total yield of potable water, litres
Y	Yield of biogas per kg of dung, m^3/kg
y	Years
α_1	Temperature coefficient of open circuit voltage, volt
α_2	Temperature coefficient of short circuit current, volt
β	Slope of the solar collector, degrees
δ	Declination angle, degrees
θ	Incidence angle of solar radiation, degrees
ρ	Albedo
φ	Latitude, degrees
ω	Hour angle, degrees
L(k)	Total instantaneous load, kW
ss	Scale factor for ethanol separation
sy	Scale factor for ethanol synthesis
σ	Wind density, m^3/kg

1. Introduction

1.1. Background and Motivation

Energy and the growth of human civilization have close link. In every aspect of modern human life there is a need of energy. Primitive men used their muscle power for their energy required for various needs like farming, movement etc. But gradually the scenario changed. Men invented machines to do various works in an easier way. These machines needed energy, mostly electricity, to run. With the industrial revolution came the age of automation evolved, i.e. the machines run on their own without any deployment of manpower. Then the demand of energy increased drastically and men was looking for more and more energy resources. Energy has a direct relationship with the human development index (HDI). The per capita energy consumption is an indicator of HDI (Gae, 2008). Over a long period, most of the energy resources were harvested from fossil fuels like coal, oil etc. But these fossil fuels have severe limitations of limited reserves. Also these fuels emit green house gases (GHG) on combustion causing local pollution and other severe global environmental damage, say, global warming. But at the same time, with the development of human civilization the demand for energy increased exponentially. With the advancement of technology men started converting energy from one form to another. Electricity emerged as the most convenient form of energy as it can be transported over long distance and can be controlled more conveniently than other forms of energy. So the demand for electricity increased with the advancement of human civilization over the ages. With several limitations of fossil fuel based power, renewable options are also explored. However, the renewable options are intermittent in nature and needs either proper storage or hybridization of several resources to meet the varying load. Hybrid polygeneration may be a suitable technology option for this purpose.

1.2. World Energy Scenario

Presently the world is mostly dependent on fossil fuels for energy. But generation of energy from the fossil fuels is not a sustainable option as the reserves of fossil fuels are limited. Moreover, they emit green house gases (GHG) during combustion to produce energy. Even with best practices, the coal based thermal power plants emit 532 g-CO_2 for each unit of electricity generated (Rydh et al 2003).These gases have severe detrimental effect, global warming. But the primary energy consumption all over the world is increasing by almost 2% every year for the last ten years (BP statistical review, 2017). **Fig 1.1** shows the share of different sources in primary energy consumption of the world (IEA, 2017).

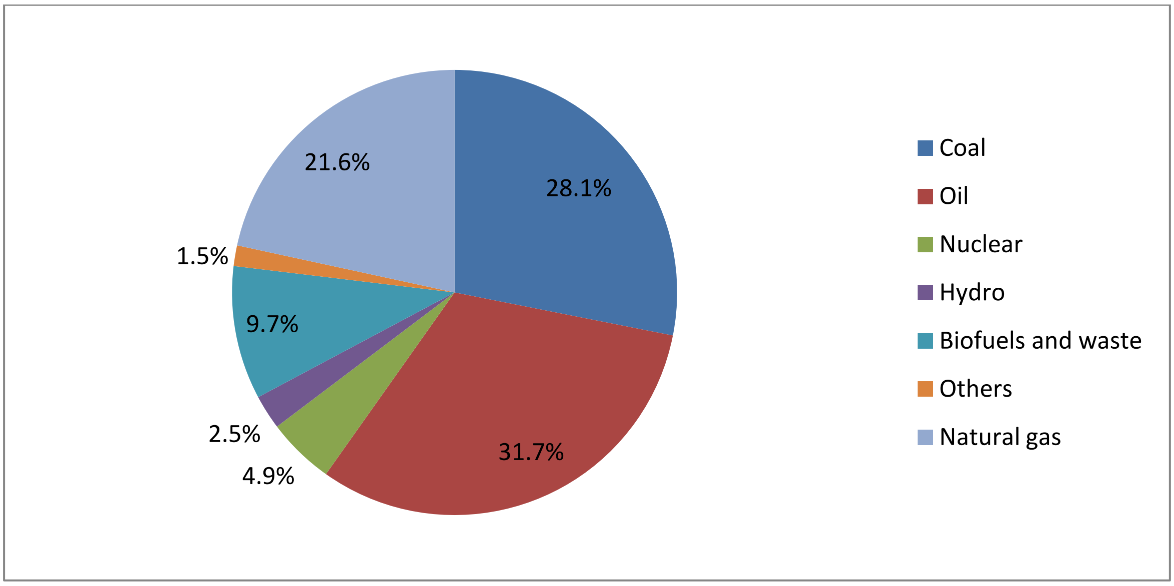


Fig 1.1: Share of different energy sources in primary energy consumption in world (IEA, 2017)

It is observed that the forerunner is oil followed by the coal. But the reserves of these resources are limiting and they emit substantial GHG through combustion. These two aspects have forced scientists and policy makers to search alternative forms of energy. World leaders met at different summits and adopted various policies to limit the GHG emission in order to protect the environment. Some of these important summits are shown in as **Table 1.1.** These meetings play the role of catalyst for the development of technologies for harvesting energy from the renewable energy resources.

Table 1.1: Various protocols for limiting carbon emission targets

Serial No	Milestones	Place	Year	Main feature
1	Kyoto Protocol	Kyoto, Japan	1997	Emission targets were set to the participating nations
2	Cancun Agreements	Mexico	2010	It was decided that the developed nations will mobilize 100 billion USD to developing nations as climate protection fund.
3	Durban Platform for enhanced Action	South Africa	2011	Opinion of legal framework formulation was considered to all members of the United Nations
4	Paris Agreement	Paris, France	2016	The climate change is considered as an urgent threat. The specific areas of fund and technology transfer of the developing nations are identified.

In all these summits the main agenda was to reduce carbon emission. Each and every nation was given a target of limiting the carbon emission to a certain level to reduce the environmental pollution effects like global warming.

1.3. Advantages and disadvantages of renewable energy

The renewable energy has the following advantages **(Tsoutsos T et al, 2005):**

- It is generally clean energy
- The operation and the maintenance cost is low
- It increases the regional/national energy independence as unlike the fossil fuel, these reserves are not confined within a particular boundary.
- Accelerates rural electrification in the developing countries.

In spite of all these advantages the renewable energy has following disadvantages:

- It is intermittent in nature i.e. the electricity can be generated when the resource is available but not when it is actually required.
- This gives rise to the necessity of suitable energy storage systems. The conventional practice is to store electricity in a battery. These batteries affect environment and economy. There are also capacity limitations.
- The initial capital investment is high.

It is noted that the renewable energy has many advantages as well as disadvantages. The disadvantages of the use of renewable energy are not only technical but also socio economic. Hence for the development of renewable energy systems suitable need based conversion technologies have to be designed.

The renewable technology is yet to be matured enough to build large scale power plants. Moreover, due to intermittent availability, storage is a big issue. Presently, the most convenient form of electricity storage is electrochemical storage i.e. to store electricity in a battery by electrochemical reaction and also release it when it is required. But the electrochemical storage has capacity, environmental and economic limitations. High cost of batteries makes the system cost high. Batteries are to be generally replaced after five years whereas most of the renewable energy systems have a life of about twenty years or more. Moreover, the disposal of the batteries is also not environmentally benign. This leads to the need of hybridization of different renewable energy systems i.e. combining various renewable energy systems like solar, biomass, wind etc into a single system. Thus, distributed generation using local resources may be another suitable option for the energy systems. These systems are designed to match several local utility demands taking into consideration the technological as well as the socio-economic and environmental constraints.

1.4. Driving policies for development of distributed generation in India

In India, Electricity Act 2003 was passed in the parliament which laid emphasis on rapid electrification of the un-electrified villages (Electricity Act, 2003). The supply of power from the large coal based power plants is not feasible always due to economic reasons as well as adverse terrain conditions. Moreover, the number of consumers in many places is very low. So it is not profitable to use grid power to electrify these villages. In such places the solar power is more relevant. After this, the Government of India has also launched many programmes like Rajiv Gandhi GrameenVidyutikaranYojna, DeendayalUpadhyayYojna to expedite the rural electrification in India. After this, the Jawaharlal Nehru National Solar Power Mission was launched which has the target of installing 20,000MW by 2022 and achieve the grid parity by the same year (MNRE, 2017). Thus in India, solar power development is mainly driven by international norms to reduce carbon footprint and rapid rural electrification. After the national policy the various states of India has also adopted solar energy policies based on the resource availability and other socio economic factors. Apart from rural electrification, to meet the international commitments of mitigating the carbon foot print many policies were taken by the Government of India for the development of the renewable energy policies. Moreover, small and un-electrified villages of India are also not suitable for grid electrification due to poor economic condition of the people as well as the adverse terrain conditions. This also led the policy makers to think of distributed generation using local resources.

1.5. Need of multi-utility systems (polygeneration) in India

Till date Indian power sector is mostly dominated by thermal power form large coal based plants. The share of power from different resources in Indian grid is as shown in **Fig1.2**.

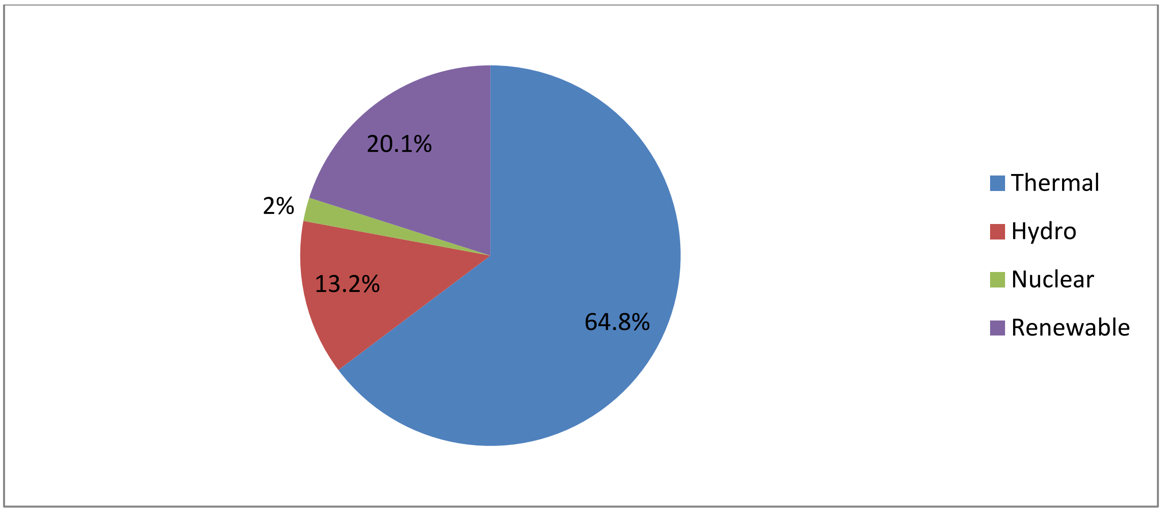


Fig 1.2: Share of different energy sources in electricity generation in India (MoP, 2017)

Though the renewable energy sources are clean, these are intermittent and dilute too. The renewable sources of energy are not available according to the demand of the consumer i.e matching the load curve. Hence storage of energy is necessary for the efficient operation. When the resource is available but the demand is low, the energy may be stored or utilized for some other purposes. Thus to patch up the mismatch between resource availability and instantaneous power demand, polygeneration may be viewed as an effective way. Moreover, in many cases, it is observed that electricity is not the only need of local people. In addition to electricity, people in the remote villages also need some basic other utilities like potable water, cooking fuel, transportation fuel etc. So if these can be supplied from an efficiently integrated single system, then it is beneficial also from the socio-economic point of view. Moreover, the overall efficiency of the system increases with the efficient system integration (Ray et al, 2017). The basic scheme of polygeneration is shown in **Figure 1.3.**

Fig. 1.3: Concept of polygeneration

1.6. Need of optimization in design of polygeneration systems in India

Polygeneration is a multi-input and multi-output system. So, the development of new systems need optimized solution with the definite objective functions and need based constraints for proper operation. Here, the optimized solution has to be chosen. For these purpose, the definite and suitable optimization algorithms are to be used for proper design and operation of the systems with possible optimization satisfying the constraints

In this thesis, several optimization studies are carried out for polygeneration systems with different inputs and need based utility outputs for several cases of Indian villages. The techno-economic optimization of different polygeneration systems using different mathematical algorithms is the main objective of this study. Realistic boundary conditions and constraints are considered depending on the technical as well as socio-economic conditions of that particular Indian village. The particular algorithm of optimization is decided based on the objective function(s) and the boundary conditions. The villages considered are located at geographically remote areas, either at the hilly locations or in the deltaic areas. In both these areas the extension of national grid is not feasible due to different socio-economic reasons.

1.7. Organization of the thesis

In chapter 1, introduction of the thesis is presented. In this section, motivation and background of the research is shown. In chapter 2, a brief literature review is presented to show the present state of the art research which is already done in this area. The objective of the work is decided accordingly. In chapter 3, single objective optimization for a remote village in Sunderban area is carried out using linear programming. In chapter 4, another optimization is carried out with another set of inputs and output utilities. In chapter 5, multi-objective optimization is carried out using metaheuristic algorithm for a polygeneration system for a village located in a hilly terrain of India. The objective functions were levelized cost of electricity, land requirement and GHG emission. In chapter 6, optimization is carried out to minimize the levelized cost of electricity using quantum inspired metaheuristic algorithm. In chapter 7, conclusions and future scopes of this study are presented.

2. Review of Earlier Works

2.1. Introduction

Presently, sustainable development is considered as the most rational goal. Energy conversion and use is a very important aspect of this sustainable goal. However, during transition from fossil fuels to renewable options, efficient and environment-friendly use of fossil fuels also has to be assured. **Fig 2.1** shows the transition of energy systems to the sustainable energy systems which is taking place in the world now.

Polygeneration is considered as a possible sustainable energy solution that may use multiple fuels with simultaneous delivery of several utilities. Overall efficiency increases significantly if the system design and integration of sub-systems are done efficiently. Moreover several alternative fuels may be used to improve resource utilization through proper fuel switching or mixing with conventional fuels. Environmental impact also reduces with higher efficiency as well as type of fuel used. Even CO_2 capture is a natural option for delivering several utilities in fossil fuel based polygenerations for liquid/gaseous fuel synthesis. Depending on desired utility outputs and optimum use of available resources, hybrid systems integrating both renewable and non-renewable resources with optimum capacity may be also sustainable.

The demand of the whole world is to now to be transformed into sustainable energy systems as far as possible from the conventional fossil fuel based energy systems. But there are certain steps regarding these which is shown in the **Figure 2.1**

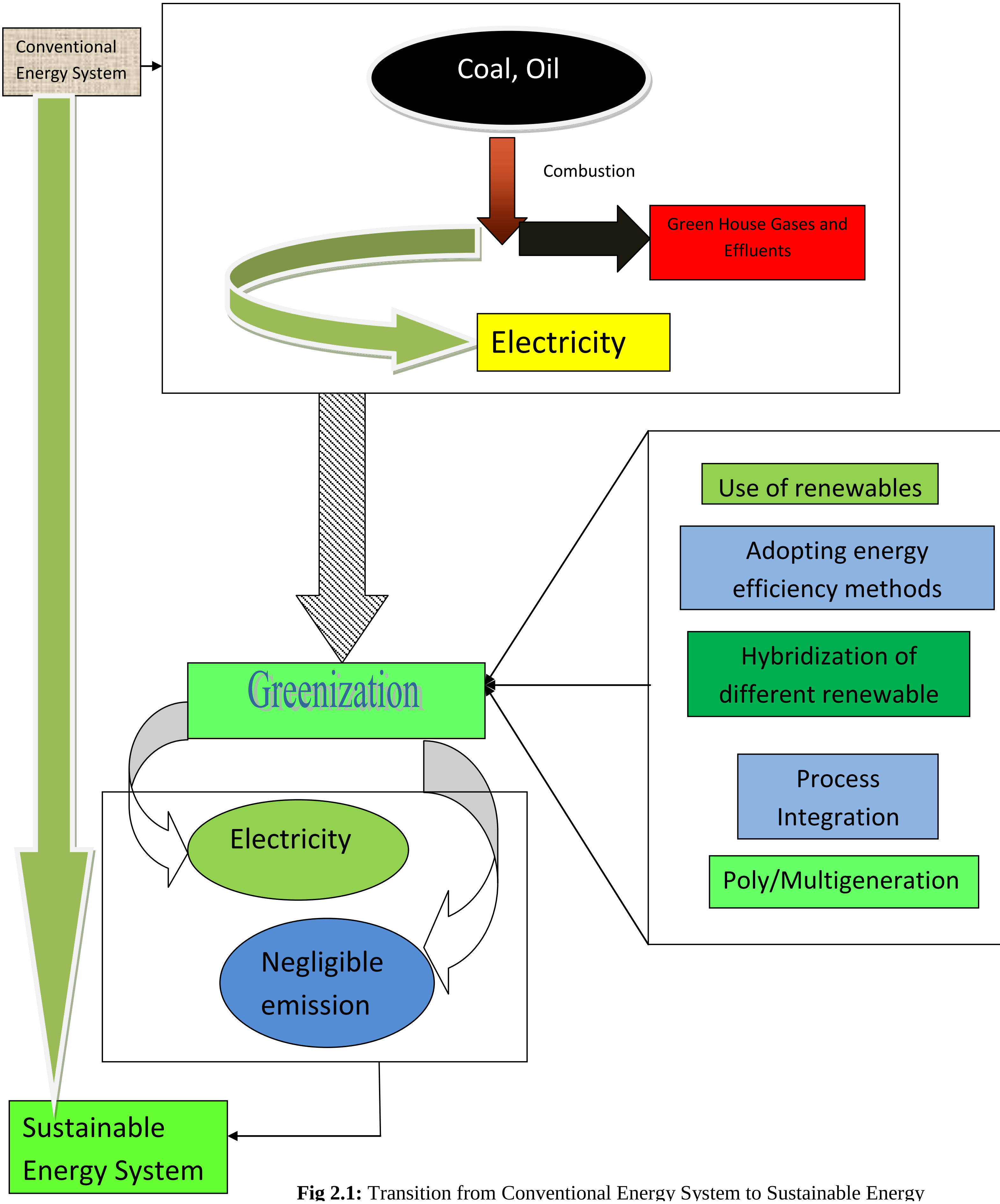


Fig 2.1: Transition from Conventional Energy System to Sustainable Energy

2.2. Basic concept towards polygeneration

Polygeneration is the process of system integration for delivering multiple utilities from a single unit to obtain an efficient multi-utility system. Though it increases system complexity, properly designed polygeneration enhances energy efficiency, reduces emission and waste, and increases economic benefit **(Serra et al, 2009)**. It is observed that with the addition of the utilities, the resource utilization is better. **Fig 2.2** shows the development of concept towards polygeneration.

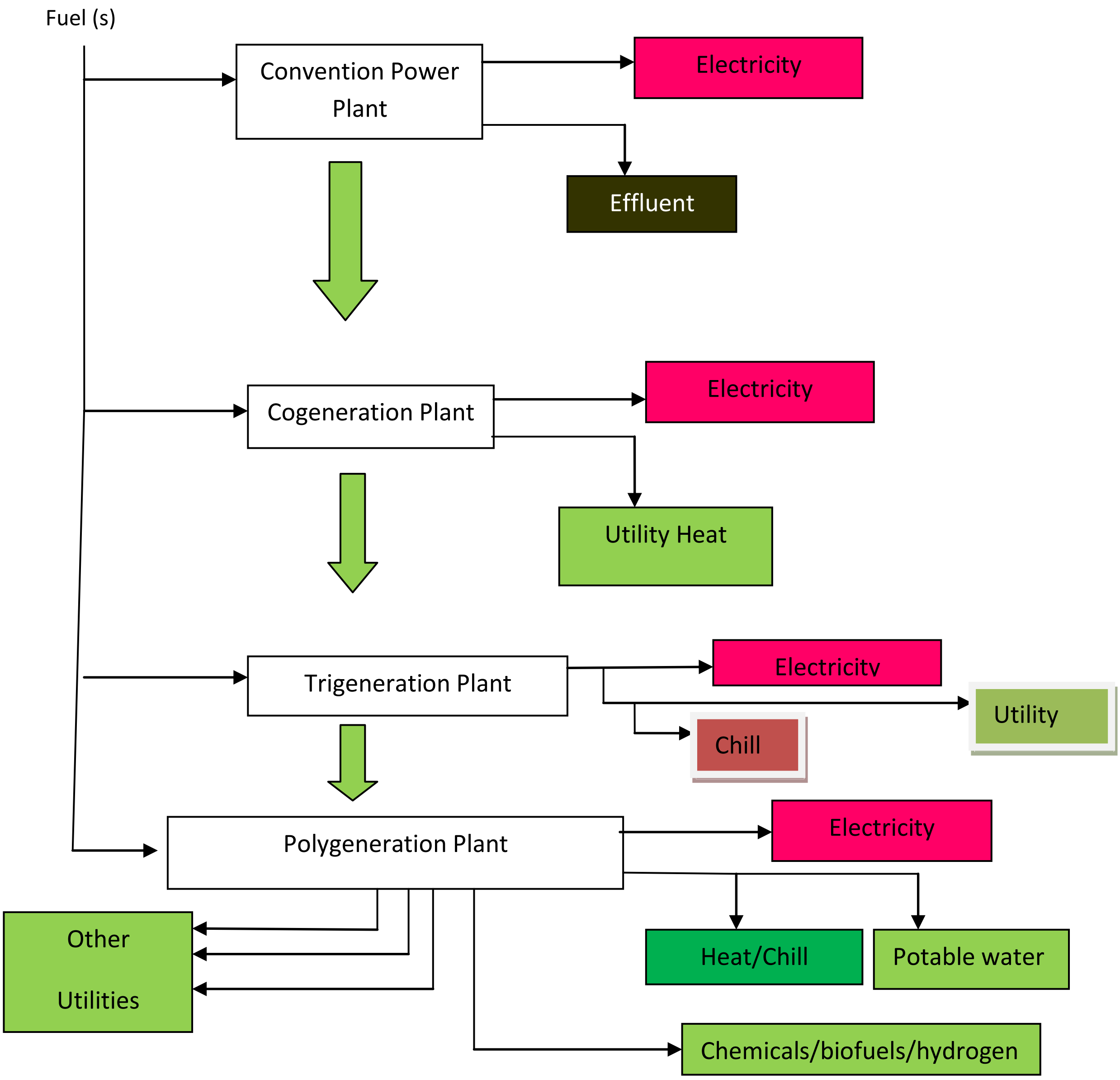


Fig 2.2: Development of concept of polygeneration

2.3. Resource estimation in polygeneration

In the development of polygeneration systems, resource estimation is a cardinal issue. Especially in the development of polygeneration in the Indian context with renewable resources, the availability of renewable resources across the whole country needs to be known.

2.4. Design and Simulation of polygeneration systems

In **table 2.1**, the various types of polygeneration systems with various inputs and output are shown. The inputs may be fossil fuels or renewable or hybridization of fossil fuels and renewable. The outputs are generated as per the local requirement.

In this chapter, a comprehensive review of reported polygenerations in literature has been compiled. This includes systems using local resources for small scale distributed generation as well as large scale (even including fossil fuels). Hybrid systems with multiple types of inputs including both fossil and renewable are reviewed. Useful polygeneration may also include outputs other than energy services (say, power, heating, cooling etc.). Polygenerations including other outputs (say, clean liquid and gaseous fuels, fertilizers, potable water etc.) are also included in this review. Performance assessment of polygeneration is multi dimensional as utility outputs are of different types. A review of possible assessment of polygeneration from muti-dimensional viewpoints is done.

Majority of the literature on polygeneration is simulation based. Practical or pilot plant projects are very few. So, table 2.1 gives a brief idea about the conversion technologies, simulation software used , the inputs and the utility outputs.

Table 2.1: Design aspect of polygeneration systems

Author (year)	**Input energy sources**	**Outputs**	**Energy conversion devices for power/electricity**	**Objectives**
Gao et al. (2008)	Natural gas	Power, methanol	CCGT	System design
De Kam et al. (2009)	Biomass	Ethanol, power, heat	Steam turbine	Aspen Plus® simulation
Rubio-Maya et al. (2011)	Natural gas, solar energy	Electricity, heating, cooling fresh water	Gas turbine, fuel cell, Stirling engine	Design optimization
Kyriakarakos et al. (2011)	Wind energy, solar energy	Electricity, water, H_2	Wind turbine, fuel cell	Simulation and optimization
Pellegrini and Oliveira Jr. (2011)	Sugarcane	Sugar, ethanol, electricity	Steam turbine	Exergy optimization
Li et al. (2011)	Coal, coke oven gas	Methanol, dimethyl ether, dimethyl carbonate	-	Simulation and exergoeconomic analysis
Chen et al. (2011)	Coal, biomass	Power, liquid fuels, chemicals	-	Optimization of process design
Ilic et al. (2012)	Biomass, molasses	Ethanol, biogas, electricity, heat	-	Optimization

Ahmadi et al. (2012)	-	Power, cooling, heating	CCGT	Multi-objective optimization
Maraver et al., (2012)	-	Power, cooling, desalinated water	Organic rankine cycle	Simulation and performance assessment
Calise et al. (2012a)	Vegetable oil, solar thermal	Electricity, space heating, cooling domestic hot water	Reciprocating engine	Dynamic simulation (by TRNsys)
Calise et al. (2012b)	Hybrid solar photovoltaic/thermal collectors (PVT)	Electricity, space heating, cooling domestic hot water	PV	Dynamic simulation (by TRNsys$^{\circledR}$)
Samavati et al. (2012)	Syngas and hydrogen	Electricity and heating	Solid oxide fuel cell	Design and simulation
Song et al. (2012)	Biomass	Ethanol, power, heat	Steam turbine	Influence of drying process
Yi et al. (2012)	coke-oven gas and coal gasified gas	Electricity, methanol, DME	CCGT	Aspen Plus$^{\circledR}$ simulation and optimization
Meerman et al. (2013)	Coal, wood, heavy oil	Power, methanol, FT liquids, H_2, urea	Gas turbine	Thermodynamic assessment (Aspen Plus$^{\circledR}$ simulation)
Li et al. (2014b)	Coal	Methanol, power	CCGT	Aspen

				Plus$^{®}$simulation
Lythcke-Jørgensen et al. (2014)	Biomass	Power, heat, ethanol	Steam turbine	Exergy analysis
Salkuyeh and Adams II (2014)	Coal	Power, methanol, DME	Gas turbine, steam turbine	Chemical looping
Narvaez et al. (2014)	Syngas	Power, methanol	CCGT	Process design for small and medium scale
Zhang et al. (2014)	Coal	Electricity, methanol	CCGT	Optimal design (MINLP)
Li et al. (2014a)	Coal	Natural gas, power	CCGT	Exergy analysis
Calise et al. (2014)	Geothermal energy, solar energy	electricity, thermal energy, cooling energy and fresh water	PV	Dynamic simulation and economic assessment
Buonomano et al. (2014)	Solar energy	Heating, cooling, electricity	PV	Design, simulation and thermo-economic optimization
Bose et al. (2015)	Coal	Power, urea, utility heat	CCGT	Process design (Aspen Plus$^{®}$ simulation)

Jana and De (2015b)	Agricultural waste	Power, heat, chill, ethanol	CCGT	Process design (Aspen Plus$^{®}$ simulation)
Jana and De (2015d)	Coconut fiber	Power, desalinated water, heat, chill	CCGT	Process design (Aspen Plus$^{®}$ simulation)
Tock and Marechal (2015)	Biomass, coal, natural gas	H_2, electricity, heat and captured CO_2	Gas turbine, steam turbine, fuel cell	Multi-objective optimization
Lythcke-Jørgensen and Haglind (2015)	Biomass (straw)	Power, heat, ethanol	Steam turbine	Design optimization
Salkuyeh and Adams II (2015)	Shale gas	Power, ethylene	CCGT	Process design (Aspen Plus$^{®}$ simulation)
Hao et al. (2015)	coal and coke oven gas	dimethyl ether, methanol and electricity	CCGT	System modeling
Calise et al. (2015)	Solar PV/T, biomass	Power, heating, cooling, fresh water	PV	Exergy analysis
Yu and Chien (2015)	Coal	SNG, ammonia, electricity	Steam turbine	Design and economic evaluation
Guo et al. (2015)	Lignite	Electricity, tar	CCGT	Simulation

Zhu et al. (2016)	Coal	H_2, power	CCGT	Modeling (dual chemical looping process)
Farhat and Reichelstein (2016)	Coal	H_2, power, urea, ammonia	CCGT	Economic modeling
Calise et al. (2016)	Solar PV/T	Electricity, space heating, chilling, hot water	PV	Dynamic simulation and thermoeconomic optimization
Kieffer et al. (2016)	Natural gas, municipal solid waste	Electricity, transportation fuel (FT)	CCGT	Techno-economic modeling
Mohan et al. (2016)	Solar thermal	Chill, clean water, domestic hot water	-	Dynamic simulation (by TRNsys) and economic modeling
Soutullo et al. (2016)	Solar thermal, PV, PEM fuel cell, biomass	Heating, cooling, electricity	PV, PEM fuel cell	TRNsys simulation and performance assessment
Rahman and Malmquist (2016)	-	Electricity, heating, distilled water		Modeling and dynamic simulation

2.5. Renewable energy based polygeneration

Renewable energy based polygeneration is either solar based or biomass based or hybridized. In **table 2.2**, various biomass based polygeneration reported in literature are included. Solar and other renewable hybridized polygeneration are shown. In the biomass based polygeneration systems both the thermochemical and biochemical routes are used. Solar energy is a form of renewable energy available almost all over the world with different intensity. It can be utilized as an energy source of polygeneration. However, polygeneration is very difficult to be achieved by only solar energy input due to low energy concentration **(Calise, 2012)**. In majority of the cases, the solar energy is hybridized with other forms of renewable energy like the biomass energy and the fuel cells to produce utility outputs as obtained from the literature and shown in **Fig. 2.3** The major renewable energy sources hybridized with solar thermal or photovoltaic collectors are biomass gasifier and fuel cells**(Gassner et al, 2016)**.As noted from this table, solar thermal collectors have more applications than solar photovoltaic collectors in polygeneration systems. The fuels cell hybridized polygeneration generally produces electricity with cooling, heating and potable water as the utilities. Biomass hybridized polygeneration system generally yields biofuels like ethanol, methanol etc with the electricity, heating and cooling as the outputs. Hybrid polygeneration helps to reduce the energy storage capacity and it has the potential to utilize multiple intermittent energy resources efficiently **(Kriakarakos, 2016)**.

Table 2.2: Biomass based polygeneration

Author	**Inputs**	**Conversion process of biomass**	**Outputs**
Li et al. (2011)	Coal, biomass	Thermochemical (gasification)	Power, methanol
Trippe et al. (2011)	Biomass	Thermochemical	FT fuel, DME,

		(gasification)	chemicals
Ng et al. (2013)	Coal, Bio-oil	Thermochemical	Power, chemicals
Meerman et al. (2011)	Coal, biomass, heavy oil	Thermochemical (gasification)	Power, methanol, FT liquids, H_2, urea
Pellegrini and Oliveira Jr. (2011)	Sugarcane	Biochemical	Sugar, ethanol, electricity
Xin et al. (2013)	cellulose, hemicellulose and lignin	Thermochemical (pyrolysis)	Char, pyrolysis oil
Spencer et al. (2013)	Solid waste	Biochemical (digestion)	Heat, hydrogen, and power
Hossain et al. (2013)	Jatropha and Pongamia	Biochemical	Electricity, food preparation, cold storage and pure water
Salomon et al. (2013)	Residue of palm oil mill	Biochemical	Bio-diesel, pellet, electricity, steam
Lythcke-Jørgensen et al. (2014)	Lignocellulose	Biochemical (Saccharification and fermentation)	Power, ethanol, heat
Ilic et al. (2014)	Biomass	Biochemical, thermochemical	Ethanol, biogas, FT diesel, DME
Chen et al. (2014)	agriculture straws (cotton stalks)	Torrefaction, pyrolysis	Char, liquid oil and biogas
Khan et al. (2014)	Biogas	Digestion	Electricity, cooking energy drinking water
Vidal and Martin (2015)	Biomass (switch grass), concentrated solar energy	Thermochemical (gasification)	Electricity, H_2, heat
Bai et al. (2015)	Biomass, solar energy	Thermal gasification	Methanol, power
Jana and De (2015b)	Agricultural waste	Thermochemical (gasification)	Power, heat, chill, ethanol

Jana and De (2015d)	Coconut fiber	Thermochemical (gasification)	Power, desalinated water, heat, chill
Yang et al. (2016)	Cotton stalk, rice husk	Pyrolysis	Charcol, biogas, woody vinegar, woody tar
Chen et al. (2016a)	Cotton stalks, rapeseed stalks, tobacco stems, rice husks, and bamboo	Pyrolysis	High quality gas fuel, phenols-enriched liquid oil, carbon-based adsorbent, biochar
Chen et al. (2016b)	Tobacco waste	Pyrolysis	Char, oil, gas
Chen et al. (2016c)	pine nut shell	Pyrolysis	Biochar, bio-oil, chemicals

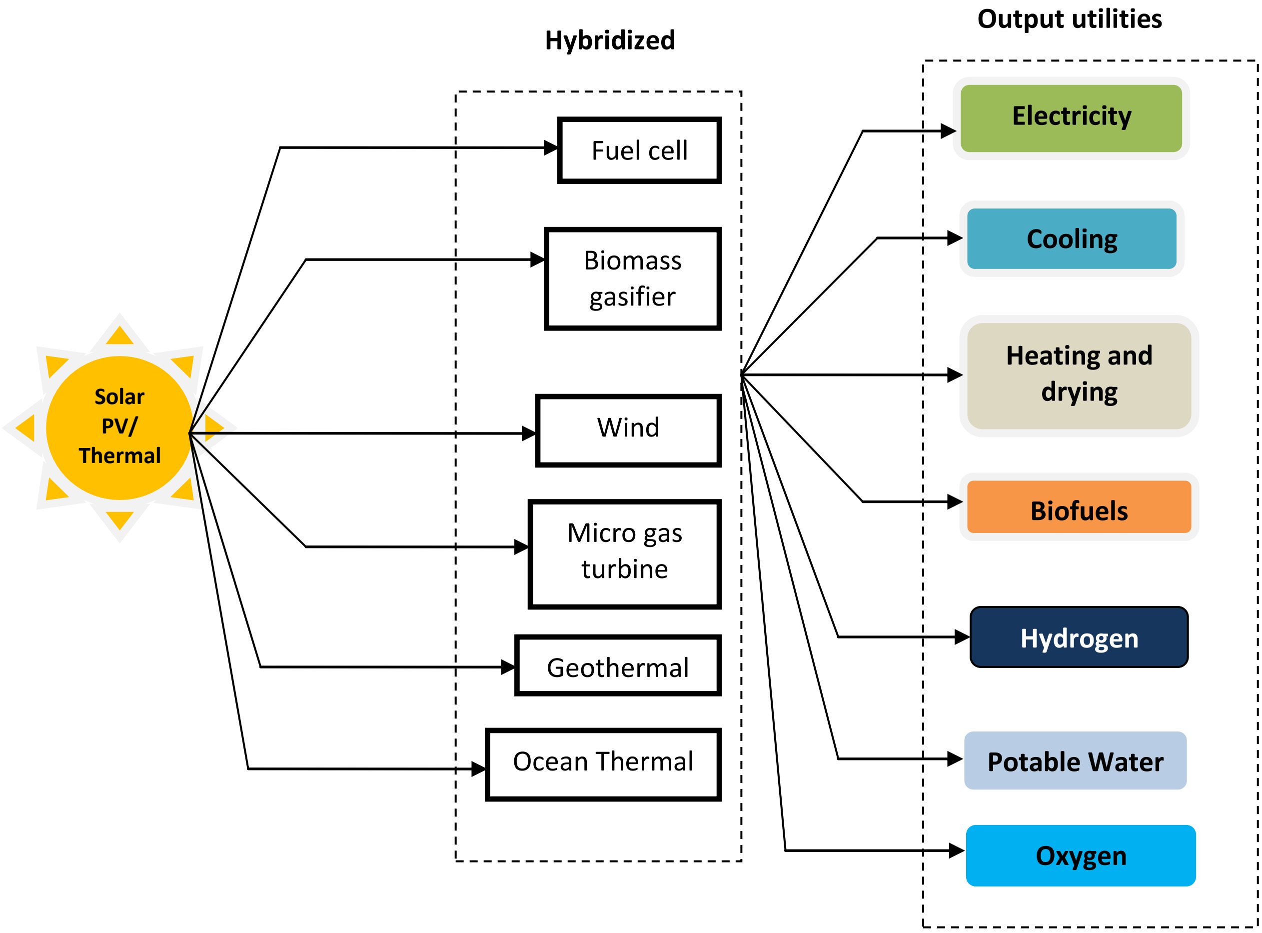


Fig 2.3: Solar hybrid polygeneration

Table 2.3: Solar hybridized polygeneration system

Author (year)	Route of solar energy utilization		Type of hybridization	Input	Output
	Solar PV	Solar thermal			
Kribbus and Mittleman (2007)	√	√	Heat engine	Solar energy	Electricity and heat
Calise (2011)		√	Solid oxide fuel cell	Solar energy	Electricity, cooling, heating
Rubio-Maya et al (2011)		√	Natural gas system and biomass gasifier	Solar energy, natural gas and biomass	Electricity, heating, cooling and fresh water
Calise et al (2012 a)	√	√	PEM fuel cell	Solar energy	Electricity, cooling, heating
Calise et al (2012 b)		√	Reciprocating engine fed by vegetable oil	Solar energy and vegetable oils	Electricity, heating and cooling
Rivalro et al (2012)		√	Wind turbine, wind turbine based micro grid	Solar energy and wind	Electricity, heating and cooling
Kaniyal et al (2013)			Coal gasification	Solar energy	Electricity and fuels
Ozturk and Dincer (2013 a)		√		Solar energy	Electricity, heating, cooling, hydrogen and

					oxygen
Ozturk and Dincer (2013 b)		√	Coal gasification	Solar energy and coal	Electricity, heating, cooling, hydrogen, oxygen and hot water
Al-Ali and Dincer (2014)		√	Geothermal well	Solar and geothermal energy	Electrical power, cooling, space heating, hot water and heat for industrial use
Aichmayer (2014)		√	Micro gas turbine	Solar assisted micro gas turbine	Electricity, hot water and cooling
Suleman et al (2014)		√	Geothermal well	Solar and geothermal energy	Electricity, drying and cooling
Bai et al (2015)		√	Biomass gasifier	Solar Energy and biomass	Electricity and methanol
Sahoo et al (2015)		√	Biomass gasifier	Solar energy and biomass	Electricity, cooling, heating and water
Khalid (2015)		√	Biomass gasifier	Solar and biomass	Electricity, cooling, hot water, heated air
Ahmadi et al (2015)	√	√	OTEC	Solar and ocean thermal energy	Electricity, fresh water, cooling and hydrogen.
Mohan et al (2016)		√	(not specified)	Solar thermal energy	Cooling, clean water and domestic hot water

Buonomano et al (2016)	√	√	The entire cogeneration system is coupled with a gas turbine co generation	Solar energy, Natural gas	Electricity, cooling ,domestic hot water
Illanes-leiva et al (2017)		√	No hybridization is made	Solar energy	Electricity, cooling, desalinated water and process heat
Belles at al (2018)		√	Biomass	Solar energy and straw	Electricity and cooling
Sahoo et al (2018)		√	Biomass	Solar energy and biomass	Electricity, cooling, desalinated water
Alavi et al (2019)		√	Gas turbine	Solar energy and natural gas	Electricity, cooling and fresh water
Calise et al (2019)		√	No hybridization is made	Solar energy	Process heat, cooling and desalinated water

2.6. Operation and control of polygeneration

Polygeneration is a multi input and a multi output system. However, supply of renewable energy is intermittent. Demands of utilities are also different. This supply and demand matching is possible through intelligent control during operation as shown in **Fig.2.4**. Literatures available for operation and control of polygeneration are shown in **Table 2.4.**In the case of renewable based polygeneration, the energy sources like solar, wind etc are intermittent in nature. The load is also variable in different seasons throughout the year. Hence a proper control system is used for the suitable operation of any polygeneration plant. In polygeneration systems, mainly the Model Predictive Control is used in most of the systems (Bracco et al, 2013). Some the systems reported in the literature have the application of supervisory control whose inputs come from supervisory control and data acquisition (SCADA) systems (Delfino et al, 2015). The application of fuzzy logic and petri net analysis proves to be better than conventional control systems (Kriakarakos, 2012). In some cases programmable logic controller (PLC) is also used. In recent times advanced numerical computational techniques are also used. The control system is mainly needed to cater to the varying seasonal load with the intermittent renewable energy resources. The PLC proves best suitable controller as the necessary changes can be made in the control logic by software applications. This also minimizes the error (Delfino et al, 2012). The different control strategies in polygeneration is shown in **table 2.4.**

Table 2.4: Operation and control of polygeneration

Author (Year)	Control/Optimisation strategy	Application area/ Objective of study
Kriakarakos et al (2012 a)	Comparison between combined fuzzy- cognitive maps petri net approach and ON/OFF approach. The petri net is used as an activator to the cognitive map.	The optimisation of the system is carried out using Particle Swarm Optimisation (PSO) algorithm.
Kyriakarakos et al (2012 b)	Fuzzy logic energy management system (FLEMS)	The size optimisation of the system is carried out using PSO algorithm.
Bracco et al (2012)	Centralised and decentralised optimal control	The smart polygeneration micro grid is connected to a data storage system for supervisory control.
Menon et al (2013)	Optimal predictive control strategies	Here the integration of heat pump and co generation facilities are studied.
Bracco et al (2013)	Model predictive control	Integration of a polygeneration micro grid with an existing grid of natural gas driven micro turbine. The polygeneration grid consists of PV, CSP, absorption chillers, storage tank etc.
Delfino et al (2015)	Model predictive control (MPC)and Programmable logic controller (PLC)	Comparison between two modes of control
Delfino et al (2015)	Tertiary, secondary and primary controller	The controllers are used for the maintenance of the voltage and frequency of the micro grid consisting of diesel generator, PV, storage system and inverters.
Bracco et al (2015)	MPC with database from SCADA	A dynamic optimisation model is used for cost minimisation and CO_2 emission reduction
Rossi et al(2016)	Simplified Management Control(SMC), Model Predictive Control (MPC), Multi Commodity Matcher(MCM)	Polygeneration microgrid couple with CHP , again coupled with solar and wind
Menon et al (2016)	Model predictive control	Optimisation of both the thermal and the electrical processes are taken into account for a micro grid connected polygeneration system.

Heinz et al (2019)	Model predictive control	Optimisation of both the thermal and the electrical processes are taken into account for a micro grid connected polygeneration system.

2.7. Optimization of polygeneration system

Polygeneration is a multi input and multi output system. Polygeneration is done with single or multiple resources to achieve cost minimization, GHG emission minimization without compromising the supply of desired quantity of the utilities. The basic area of optimization is shown in **Fig 2.4.**The intelligent demand sid and the supply side management requires optimization. Several publications are available on optimization of polygeneration as shown in **Table2.5**. To design the polygeneration systems the numerical optimization techniques are used mainly to proper sizing of the components, judicious use of resources to obtain maximum economic and environmental benefits. Maximum possible combinations are taken in consideration while designing the polygeneration system. In the design of a polygeneration system mainly multi objective optimization techniques are used. In most of the cases constrained optimization is used. Mixed Integer Linear programming is used for the proper sizing of the components of the polygenerations. Some of the objective functions have to be minimized and some have to be maximized. Non conventional optimization techniques like multi objective evolutionary algorithm and Particle Swarm Optimization (PSO) yields better results in some cases than the conventional optimization algorithms. In non conventional techniques often a set of solutions are found out. Application of fuzzy logic in the yields better results in the optimization problems.

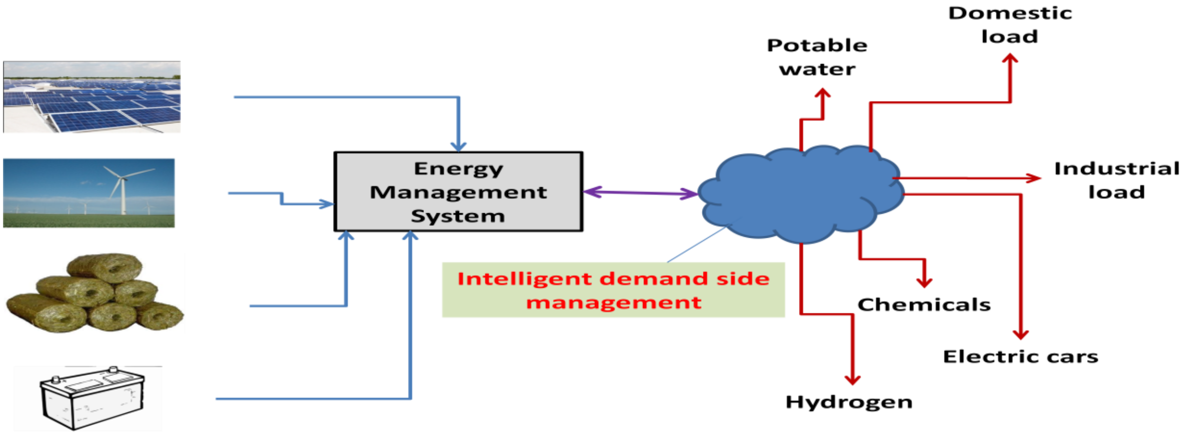


Fig 2.4: Need for optimization of polygeneration

Table 2.5: Optimization algorithms in polygeneration

Author (year)	**Algorithm used**	**Input**	**Output**
Liu et al (2007)	Mixed integer linear programming (MILP)	Coal, natural gas, biomass	Methanol and electricity
Piacentino and Cardona (2008)	Multi obejective optimisation (MOO) using heuristic algorithms	CHP prime mover	Electricity, heating and cooling
Liu et al (2009)	Mixed integer optimisation	Coal	Electricity and methanol
Rubiyo-Maya et al (2011)	Mixed integer non linear programming	Natural gas and solar	Electricity, heating, cooling and potable water
Fazlollahi and Marechal (2011)	Multi objective optimisation using MILP and Multi objective evolutionary algorithm (MOEA)	Biomass	Electricity and heat
Ahmadi et al (2012)	Evolutionary algorithm	Compressed air and natural gas	Electricity, heating, cooling and hot water
Bracco et al (2015)	Dynamic optimisation	Natural gas and solar	Electricity and cooling
Lythcke-Jørgensen and Haglind (2015)	Constrained linear otpimisation	Biomass (wheat straw)	Ethanol, heat and electricity
Karavas et al (2015)	Fuzzy Cognitive Maps	Solar, Wind, fuel cell	Electricity, hydrogen, desalinated water
Sigarchain et al (2016)	Particle Swarm Optimisation (PSO)	Solar, LPG	Electricity and heat
Lythcke-Jørgensen et al (2016)	Characteristic Operating Pattern Method	Coal	Electricity, heating, cooling
El-Emam and Dincer (2017)	Multi objective evolutionary algorithm	Solar , biomass	Electricity, cooling and hydrogen

2.8. Scope of present study

The review of literature shows that there is not much reported literature in the area of application of metaheuristic and quantum inspired metaheuristic techniques of optimization in the design of polygeneration systems. In this study, the systems are designed to meet the local electricity demand for location specific off grid Indian villages and catering to the local essential utility needs of the villagers considering not only the technical but also the socio-economic condition of the villagers. The techno-economic optimization is carried out to determine the size or the capacity of the components of polygeneration.

3. Polygeneration for an off-grid Indian village: optimization by economic and reliability analysis

3.1. Introduction

Grid based power supply from the large/very large power plants is the existing practice to meet the electricity demands in most parts of India. Moreover, coal based thermal power has the 60 % share in the Indian grid power mix (Ministry of Power, Government of India, Executive summary power sector, 2014).The announced policy of the Government of India (GoI) for a long term is to provide electricity to all the Indian villages as access to electricity plays a pivotal role in the social and economic development of the villagers. The Indian Parliament passed the Electricity Act in 2003 which mentioned for the first time the scope of rural electrification in a law (Modi, 2005). That was the beginning that the GoI started thinking about the decentralized distributed generation (DDG) systems to supply electricity to the villages. Subsequently, the Rajiv Gandhi Grameen Viduytikaran Yojna (RGGVY) was formulated by the GoI in 2005 to reach power to the Indian villages (Planning Commission, Evaluation Report on Rajiv Gandhi Grameen Vidyutikaran Yojana, 2014). In 2014, the GoI announced the Deendayal Upadhyay Gram Jyoti Yojna to carry forward the task of RGGVY in a faster manner (Deendayal Upadhyaya Gram Jyoti Yojana).In 2015 it has launched the Ujwal Bharat programme to reach 24×7 power for all people of India by 2019 (Government of India, 1st Year achievements and initiatives of Ministry of Power, Coal and New & Renewable Energy, 2015). The use of DDG systems for providing power in rural areas was advocated in the Electricity Act, 2003. It has found utmost importance in all the subsequent policies framed by the Indian Government. Under Village Electrification programme, Ministry of New and Renewable Energy (MNRE) has identified 12771 villages across the country where the grid connectivity is either not possible or economically not viable due to the terrain conditions (Oorja, 2013).

Providing electricity from coal based thermal power plants may not be sustainable in the long run. Electricity generated from thermal power plants emits 1.03 tonnes of CO_2- equivalent/MWh (Central Electricity Authority, Carbondioxide Baseline Database for Indian Power Sector, 2014). Moreover the per capita energy consumption (PEC) in India had a cumulative annual growth rate(CAGR) of 4.53% from 2006 to 2014. On the contrary, the increase in the coal reserve of the countryis only 0.7% in 2013-2014 (Government of India, Energy Statistics, 2015).Therefore fuel switching from coal to renewable may be a sustainable option for energy security within a definite time frame for this country. The industrial activities of the modern civilization including the use of fossil fuels have raised the carbon dioxide level from 280 ppm to 400 ppm over the last 250 years (NASA Climate Consensus). After the Paris agreement held in December 2015, India has a target of reducing the greenhouse gas (GHG) emission by 30% to 35% from the amount that India emitted in 2005. India has also planned to increase by 40% transition of power from fossil fuel based power plants to renewable by 2030 (NRDC, The Paris Agreement on Climate Change).

Generating power from renewable resources of energy are generally environment-friendly. Nevertheless, it has to comply with the economic feasibility and social acceptability. Regarding this subject, the biomass resources are abundantly available in many Indian villages. The total national amount of surplus biomass amounts is 120-150 metric tons per annum having the potential to generate 18000 MW of electric power (MNRE). In spite of huge potential, this resource is not efficiently harnessed due to non-deployment of suitable technologies. The proper utilization of these resources with proper multi utility system may be the suitable option for social and economic development of the villages. The biomass supply may vary with the seasons. Hence this may be coupled in hybrid mode with other forms of renewable energy such as solar energy to provide an optimum solution. This will also help to produce other utilities like bio fuels etc. that add to the value of the project.

Francesco Calise et al (Calise et al., 2014)designed a polygeneration system including a geothermal well, solar thermal and photovoltaic collectors, a single effect vapour absorption cooling system and auxiliaries like heat exchangers, storage tanks etc. They developed a system to supply electricity, cooling, heating and fresh water. They also designed a control strategy for the optimum supply of all these. It was observed that the profitability of the system was highest when the need of fresh desalinated water increased. This system was suitable where the water was scarce. Zbigniew Chimel et al (Chmiel and Bhattacharyya, 2015) designed a hybrid generating system using diesel generator (DG), wind turbine, photovoltaic array and a battery bank for supply of electricity to the people of the remote Island of Isle of Eigg in Scotland. The result showed that the over sizing of the system adds to the system reliability but the cost is also increased. Hence suitable sizing of the components based on the available resources is very essential for the optimum operation of the system. Xiongwen Zhang et al(Zhang et al., 2013)simulated a hybrid energy system comprising of a DG set, PV panel and a battery bank for a decentralized power generation system for an off grid village. This chapter proposes a methodology of sizing the various components based on power dispatch simulations with the objective of minimizing the cost of energy. Kyriakarakos et al (Kyriakarakos et al 2013) designed a system using fuzzy logic to optimize the size of the installed components for supplying the hydrogen fuel for transportation, potable water, space heating, cooling and the electricity. For this study advanced computational techniques like fuzzy logic have been used to determine the optimized size of the systems. Hossain et al designed (Hossain et al., 2013)a polygeneration system with a 9.9 kW compressed ignition engine running on plant oil. It produced ice by means of adsorption refrigeration powered by engine jacket heat and the exhaust heat of the engine was used to food preparation and desalinated water using multiple desalination systems. Jana and De (Jana and De, 2015) designed a biomass based polygeneration system delivering power, ethanol, cooling and heating which has a payback period of less than five years. Mohan et al(Mohan et al., 2016) experimentally investigated a novel solar thermal polygeneration unit for catering the cooling need and safe drinking water supply for the Middle East and African countries. The plant had a payback period of 9.08 years with a net cumulative savings of 454000 USD. It was observed that the use of locally available good quality energy resources enhanced the value of percentage of Human Development Index (HDI) by 16% to 18% than its initial Figure in Indian conditions (Ray et al., 2016).Kong et al described the use of thermo chemical cycling in designing a polygeneration system (Kong et al., 2016). This serves as a means of converting the solar energy and storing it in the form of chemical fuels which is more convenient than battery storage. The input of the polygeneration process is the waste heat of the downstream of gases like carbon dioxide in the downstream of the methanol production process and solar energy. The output of the polygeneration process is power and methanol. Khalid et al deisgned a polygeneration system consisting of a wind turbine, concentrated solar collector, organic Rankine cycle and a ground source heat pump. The polygeneration system supplies electricity, hot water, heating and cooling utilities. A techno economic analysis was performed by this group. The levelized cost of electricity (LCOE) was found out to be 0.181 USD perkWh. The energy and the exergy efficiencies were found out to be 46.1% and 7.3% respectively (Khalid et al., 2016).

With depleting fossil fuel resources and increasing greenhouse gas (GHG) emission, search for alternative options for power or even multi utility systems using renewable local resources is emerging as efficient option. This becomes even more important for remote location where grid power is not economically feasible. For this reason decentralized generation is a possible option. Optimization of these systems helps to reduce the cost of utility. For distributed system in rural areas, energy supply at affordable cost is necessary. Optimization of such system may be done from different viewpoints and minimum cost or maximum profit is one of the most important criterions for optimization of such system. In this chapter, a hybrid polygeneration has been proposed to meet the energy needs of a representative village of India. The solution to this need is optimized with the annualized profit maximization or the LCOE minimization as the objective function using locally available solar and biomass resources. The constraints of this optimization are the maximum reliability of power supply and availability of the local resources. The dependent variable is profit or LCOE. The independent variables are the cost of solar module, cost of biomass gasifier, cost of straw, price of ethanol, price of wasted heat recovery vapor absorption system. The study is carried out for Sunderban area of the state of West Bengal, India. This region is a deltaic region surrounded by canals and creeks. The adverse terrain conditions have made this area difficult to be accessed by the national grid. A comparative study of the reduced CO_2 emission reduction for this decentralized power generation against the alternative means by using diesel generator sets is studied here. The linear programming method is used for determination of the optimum size of the biomass gasifier, solar module and ethanol production units. The vapor absorption cooling system is integrated in the polygeneration for preservation of agricultural products of a typical Indian remote village. The capacity of the vapour absorption system is chosen in such a way that it can store the amount of agricultural products that will be consumed by the villagers in three days. Straw is selected as the biomass resource because it is available in abundance in this area with definite possibility of supply (Indian Institute of Science, Biomass Resource Atlas of India). The decrement of LCOE as a result of hybridization and the process integration to get different utilities is shown here.

3.2. Materials and methods

A polygeneration system has been proposed to cater to the energy needs of the villagers of an off-grid village in Sunderban area of the state of West Bengal, India with the locally available resources say straw and solar energy. The electricity generated is supplied locally. The system is optimized by varying the size of the solar module and the ethanol producing units to maximize the annualized profit without compromising the reliability of the electricity supply. The ethanol generated is another utility output. The ethanol can be used as a transportation fuel in the rural areas. The Sunderban area is scattered by canals and creeks. So it is difficult to transport conventional transportation fuels there. Hence, the locally generated ethanol can serve as a suitable transportation fuel for the villagers. The vapor absorption cooling system is used for preservation of cereals and vegetables mostly during summer and the rainy seasons when the local temperature is relatively higher (above ~ 35^0C) with a relative humidity above 80% (Indian Institute of Science, Biomass Resource Atlas of India).The biomass is collected locally and transported to the biomass gasifier for use. It is fed to the biomass gasifier after drying and subsequent processing. The solar module is installed south facing with the horizontal inclination angle equal to the latitude of the place ($\sim 22^0$) under study.

3.2.1. System Description

The proposed polygeneration system consists of the biomass gasifier, solar photovoltaic(PV) module, ethanol synthesis and separation unit and a vapor absorption cooling system as shown in **Figure. 3.1**.

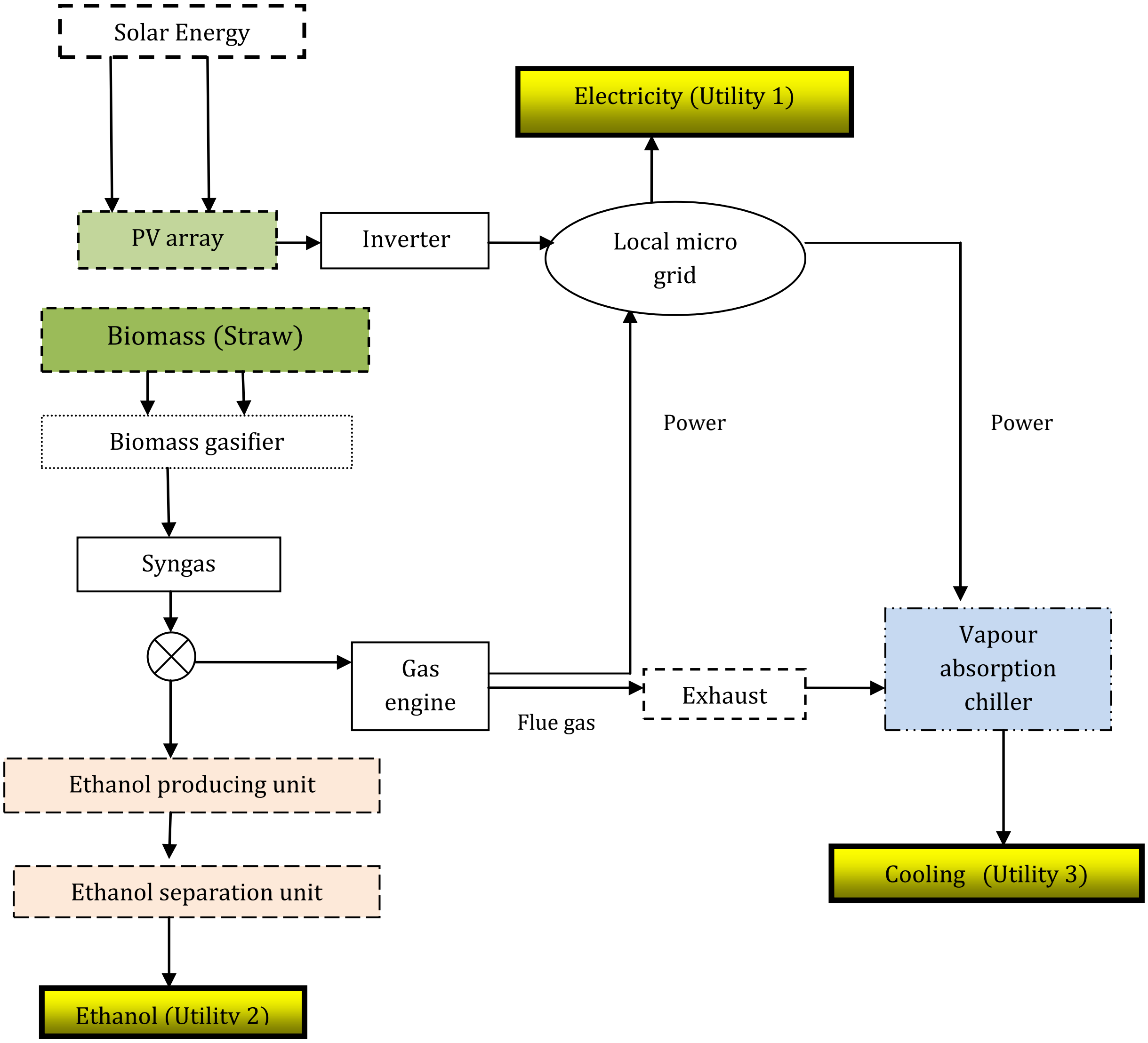
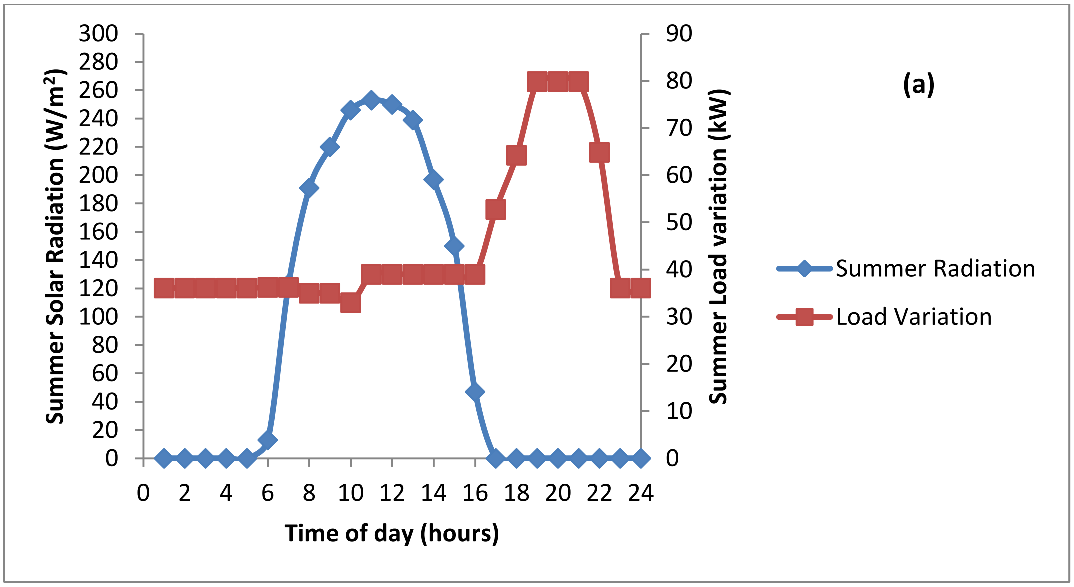
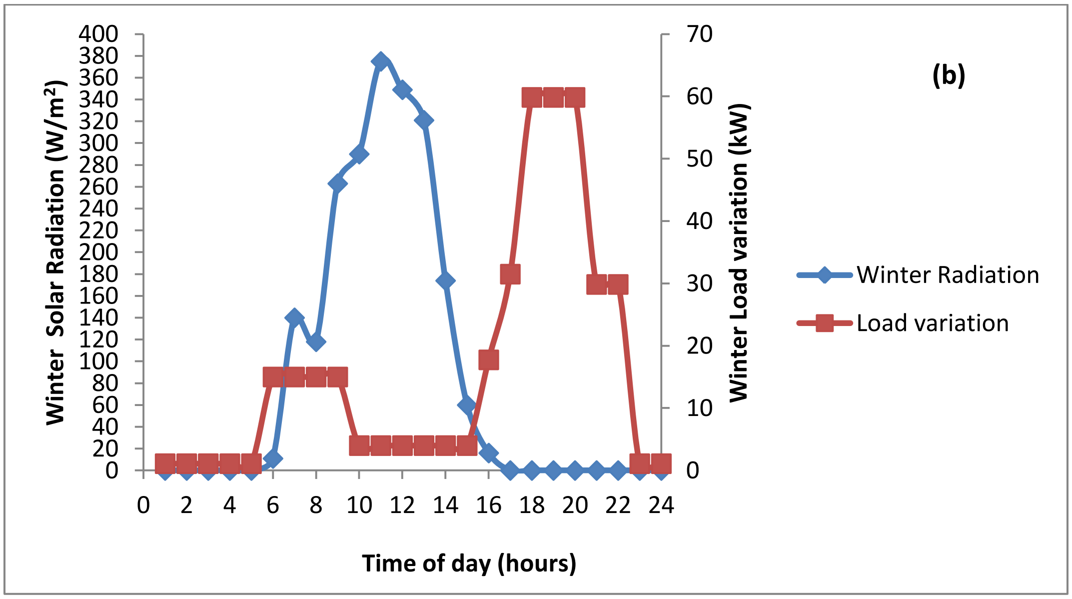


Figure 3.1: Schematic of polygeneration process

In the study area load is mostly domestic as industries even in small sizes are virtually nonexistent and people mainly depend on agriculture, fishing and forest products for their livelihood. The domestic load reaches its peak in the evening irrespective of seasons as shown in **Figures 3.2(a), 3.2(b) and3.2(c)**.





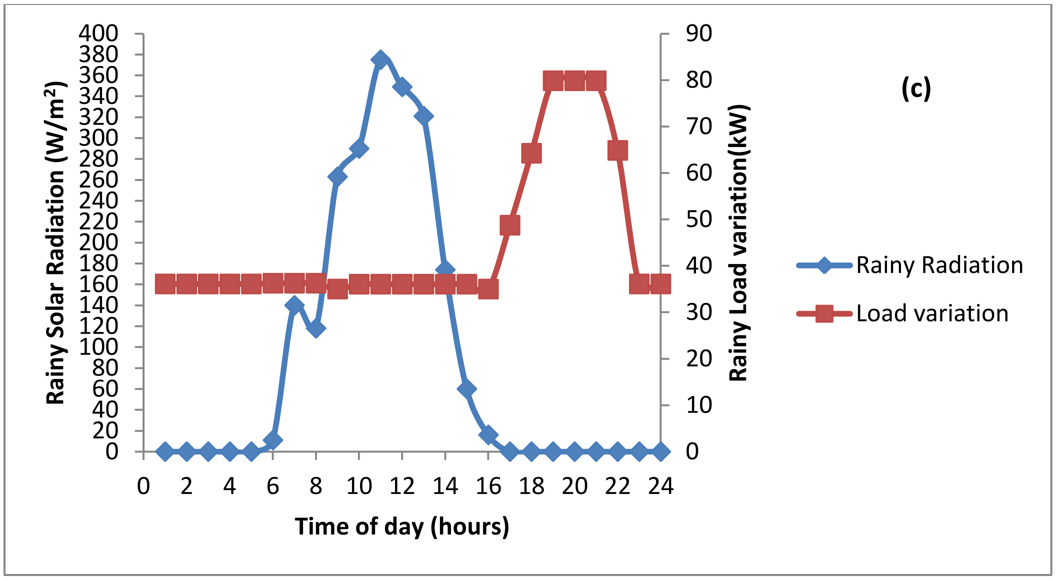


Figure 3.2: Variation of solar radiation of Sunderban with the load curve for Sunderban area (a) summer season (b) winter season (c) rainy season

In the evening, the entire electricity demand of the villagers is met up by the biomass power. The straw is gasified in a gasifier leading to the production of the syngas. The syngas is fed to a gas engine coupled with a generator to generate electricity. The waste heat from the exhaust of the gas engine is used to run a vapour absorption cooling system. During the daytime, the PV module also supplies power to the locality. The solar module generates power when the solar insolation is incident on it. So the power to the micro grid as shown in Figure3.1 comes from both the solar module as well as the gas engine. The electricity demand is also lower during daytime than the evening in absence of the lighting load. Moreover, the solar module also adds power to meet the load. So during day time, there is excess syngas which is used to produce ethanol. During this period, a minimum amount of biomass power has to be generated by the gas engine to supply the waste heat from its exhaust, required to run the vapour absorption cooling system. Small amount of electricity (0.65 kW) is also required to run the vapour absorption cooling system. Thus the three utilities say, electricity, ethanol and cooling are produced matching the demand varying over days and seasons.

3.2.1.1. Photovoltaic module

The module is installed at an orientation (south facing) to receive maximum radiation. The power generated by the solar module is given by the following equation

$$P_{solar} = \frac{PV(m) \times R(i)}{1000 \times 1000} \times \eta \times .01 \tag{3.1}$$

Where, P_{solar} is the power output of the solar module at the ith instant in kW, $PV(m)$ is the rated power output of the module at 1 Sun i.e. 1000 W/m^2 intensity and $R(i)$ is the radiation at the ith hour of the day (in W/m^2) which is taken from the India Solar Resource Data of National Renewable Energy Laboratory (NREL), USA (India Solar Resource Data).

3.2.1.2. Biomass gasifier

Straw is used as the feedstock to the biomass gasifier to generate the syngas which is fed to the gas engine to generate electricity. The waste heat from the gas engine is utilized to run the vapor absorption system.

$$P_{biomass}(k) = L(k) - P_{solar}(k) \tag{3.2}$$

Where $P_{biomass}$is the biomass power output at the kth instant, $L(k)$ is the load at the kth instant and $P_{solar}(k)$ is the power output of the solar module at kth instant. So during night when the power generated by the solar module is zero then

$$P_{biomass} = L(k)$$

3.2.1.2.1. Straw feed to the biomass gasifier

The straw input (S_{in}) to biomass gasifier is calculated using empirical relation of an Indian company (Jana and De, 2015c).

$$S_{in} = 9 \times \left(\frac{P_{biomass}}{10}\right)^{0.65} \times \left(\frac{CV_{straw}}{CV_{wood}}\right) \tag{3.3}$$

Where $P_{biomass}$the power output of the biomass gasifier, $CV_{straw}$is the calorific value of straw and $CV_{wood}$is the calorific value of wood (Ankur Scientific Energy Technologies Pvt Ltd).

3.2.1.3. Ethanol production and separation unit

The excess producer gas which is not used to produce the electricity in the gas engine generator is used to produce ethanol in the ethanol synthesis unit. Ethanol is produced in the ethanol synthesis unit by the direct hydrogenation of CO by the reaction shown below (Jana and De, 2015).Carbon monoxide and hydrogen reacts under certain temperature and pressure conditions to form the ethanol along with the production of water and heat.

$$2CO + 4H_2 \leftrightarrow C_2H_5OH + H_2O + \Delta H \tag{3.4}$$

3.2.1.4.Catalyst requirement per year

In the syngas, there must be the desired molar ratio (2:1) of H_2 and CO. This is achieved by water gas shift reaction. The MoS_2 catalyst is needed to increase the rate of the water gas shift reaction (Pearles et al., 2011).

$$C_y = \frac{Eth_y}{Eth_c} \tag{3.5}$$

Where $C_y$the yearly catalyst requirement, $Eth_y$is the ethanol produced per year and is $Eth_c$the ethanol yield per kg of the catalyst.

After synthesis, the ethanol is separated from the mixture of ethanol, water and unconverted syngas. The water is taken out and the unconverted syngas is again recycled to the ethanol synthesis unit to produce ethanol. The details of the process are described in an earlier work by the same research group of the same institute (Jana and De, 2015).

3.2.1.5. Waste heat recovery vapor absorption cooling system

The waste heat generated by the gas engine is utilized in the waste heat recovery vaporabsorption system for the cooling purpose. The waste heat (WH_{ge}) generated from the gas engine is estimated as follows (Bureau of Energy Efficiency, Energy Efficiency In Electrical Utilities, 2010).

$$WH_{ge} = E_{ge} \times F_g \times F_{sp} \times (t_g - 180) \quad (3.6)$$

Where E_{ge} is the electricity output of the gas engine, F_g is the amount of the flue gases generated per kWh of electricity generated, F_{sp} is the specific heat of the flue gas and t_g is the temperature at the exit of the turbo generator.

Therefore the minimum amount of waste heat required to run the vapor absorption system is given byEqn.3.7

$$WH_{VAM} = \frac{WH_{ge} \times F_g \times F_{sp} \times (tg - 180)}{COP} \quad (3.7)$$

3.2.2. Load curve formulation

The load curve is the variation of electricity consumption over a full day. The curve is required to design a utility system as it provides the magnitude of the power varying with time that has to be supplied. In Indian villages the load is mainly residential but the agricultural load due to water pumping is also there in summer and the winter seasons but it is negligible in the rainy season as this region has a substantial rainfall of about 1920mm (Sundarban Biosphere Reserve). The magnitude of the load depends on the number of households, appliances used by them and the season. Figures 3.2(a), (b) and (c) show the variations of load and the solar radiation in three seasons. The electrical appliances used commonly by the villagers and their respective power consumption are shown in Table 3.1.

$$TL = DL + AL + SL \quad (3.8)$$

where, TL is the total load, DL is the domestic load, AL is the agricultural load, SL is the street light load.

Table 3.1: Parameters for load curve formulation

Total Population of the village	1000
Total number of households	250

Gadgets used	Wattage	Number per household
Tubelight	55[a]	2
Incandescent bulb	60[a]	1
Mobile charger	5[b]	2
Fan	60[a]	2
Street light (Taubelight)	55[a]	20 in total village
Agricultural pumpset	400[c]	5 in total village

[a] Data is obtained from West Bengal State Electricity Distribution Company Limited (National Renewable Energy Laboratory).

[b] This is obtained from the power rating of the charger of some standard manufacturers in India

[c] This data is obtained from a report of Ministry of New and Renewable Energy, Government of India (Sinha and Chandel, 2015).

3.2.3. Economic modeling

An economic model is a simplified description of reality, designed to yield hypotheses about economic behavior that can be tested (International Monetary Fund). For energy systems, the economic planning has to be made to make the new technologies economically feasible and socially acceptable to the villagers. The basic data for economic calculation is shown in **Table 3.2.**

Table 3.2: Basic parameters for economic calculations

Serial No	Parameter	Value
1	Cost of straw	8 INR/kg [a]
2	Cost of PV module	53 INR/Watt-peak [a]
3	Cost of ethanol	40 INR/liter [a]
4	Cost of MoS_2 catalyst	720 INR/kg [a]
5	Operating hours per annum	8760 hours
6	Electricity tariff	4.36 INR/kWh [a]
7	Plant life	20 years
8	Bank Discount Rate	10%[a]
8	Capital recovery factor	0.1175
9	Cooling cost	20 USD/MM Btu [a]
10	COP of vapour absorption system	0.7[a]
11	Plant life	20 years [a]
12	Scale factor for biomass gasifier	0.65[a]
13	Ethanol productivity of MoS_2	300 g/kg-catalyst/h[a]
14	Catalyst cost	11.57 USD/kg [a]
15	Scale factor for ethanol synthesis	0.8[a]
16	Scale factor for ethanol separation	0.7[a]
17	Cost of inverter	30 INR/Watt-peak[b]
18	Efficiency of inverter	95%
19	Efficiency of PV cell	16%
20	Maintenance cost of solar module	0.5%[c]

21	Maintenance cost of biomass gasifier	5%[d]
22	Maintenance cost of gas-engine generator	10%[d]

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[a] This is taken from a previous published work of the same group (Jana and De, 2015).
[b] This data is taken from some local suppliers.
[c] This data is taken from a published literature (Kreith, 2015).
[d] This data is taken from a published literature (Dutta et al., 2009).

3.2.3.1. Cost of biomass gasifier

The cost of the biomass gasifier is available in different scales. So scaling is necessary for getting the initial cost of the biomass gasifier by the following equation (Kreith, 2015).

$$C_{eqb} = C_{eqa}\left(\frac{Capacity_b}{Capacity_a}\right)^S \tag{3.9}$$

Where C_{eqa} is the cost of biomass gasifier of capacity a, S is the scale factor for biomass gasifier and C_{eqb} is the cost of biomass gasifier of capacity b.

3.2.3.2. Cost of vapor absorption system

The cost of a 3TR vapor absorption chiller machine with the waste heat recovery system is as follows.

$$TC_{WHRVAM} = 1456000\ INR \tag{3.10}$$

$TC_{WHRVAM}$is the total cost of Waste Heat Recovery Vapor Absorption Cooling Machine along with the waste heat recovery system. The price is obtained from a quotation given by an Indian company.

3.2.3.3. Cost of ethanol synthesis and separation

The syngas is fed to the ethanol synthesis unit for ethanol production. Pure ethanol is obtained after separating it from the water and unconverted syngas in the ethanol separation unit (Dutta et al., 2009).

$$TC_{esyn} = 7.4 \times 10^6 \times \left(\frac{E_{thy}}{31176000}\right)^{S_e} \tag{3.11}$$

where,TC_{esyn} is the total cost of the ethanol synthesis unitE_{thy} is the total ethanol synthesized per year and$S_e$is the scale factor for the costing of the ethanol synthesis equipment.

$$TC_{esep} = 64.4 \times 10^6 \times \left(\frac{E_{thy}}{31176000}\right)^{S_s} \tag{3.12}$$

$TC_{esep}$is the total cost of the ethanol separation unit, $E_{thy}$is the total ethanol synthesized per year and$S_s$is the scale factor for ethanol separation unit.

3.2.3.4. Optimization Equations

The linear programming approach is adopted here to find out the optimized sizes of the system components from various combinations of capacities of solar PV, biomass gasifier, ethanol producing units and vapour absorption cooling system. The optimization is carried out based on cost. The cost optimization is done for a whole year considering the seasonal variation. The thermodynamic optimization data is taken from a previously published work of the same group (Jana and De 2015). The detailed steps of optimization are shown in flow charts in Figures 3.3(a) and (b).

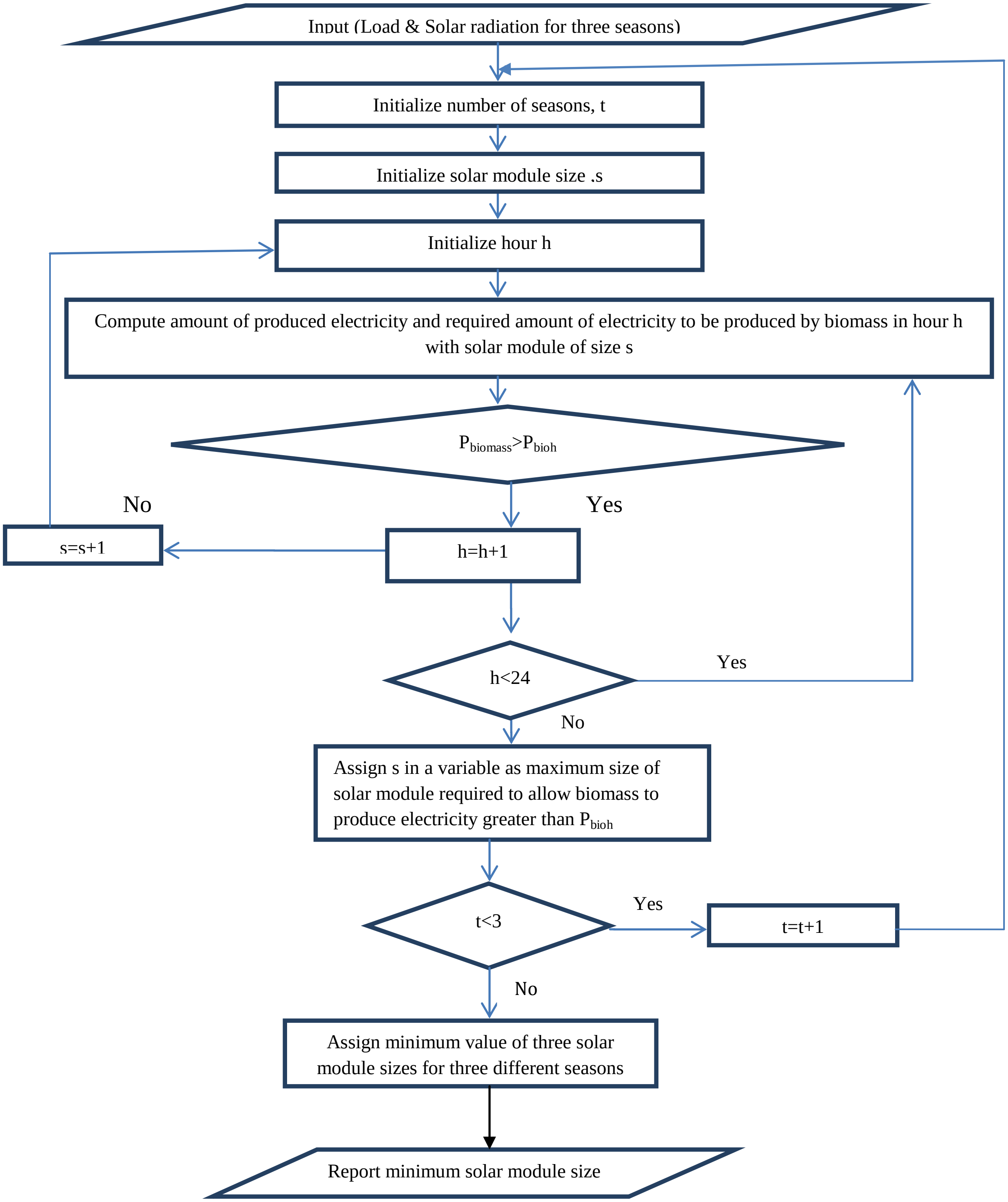

Figure 3.3(a): Flow chart for determination of solar module when there is no shortage of supply of waste heat to WHRVA*M*

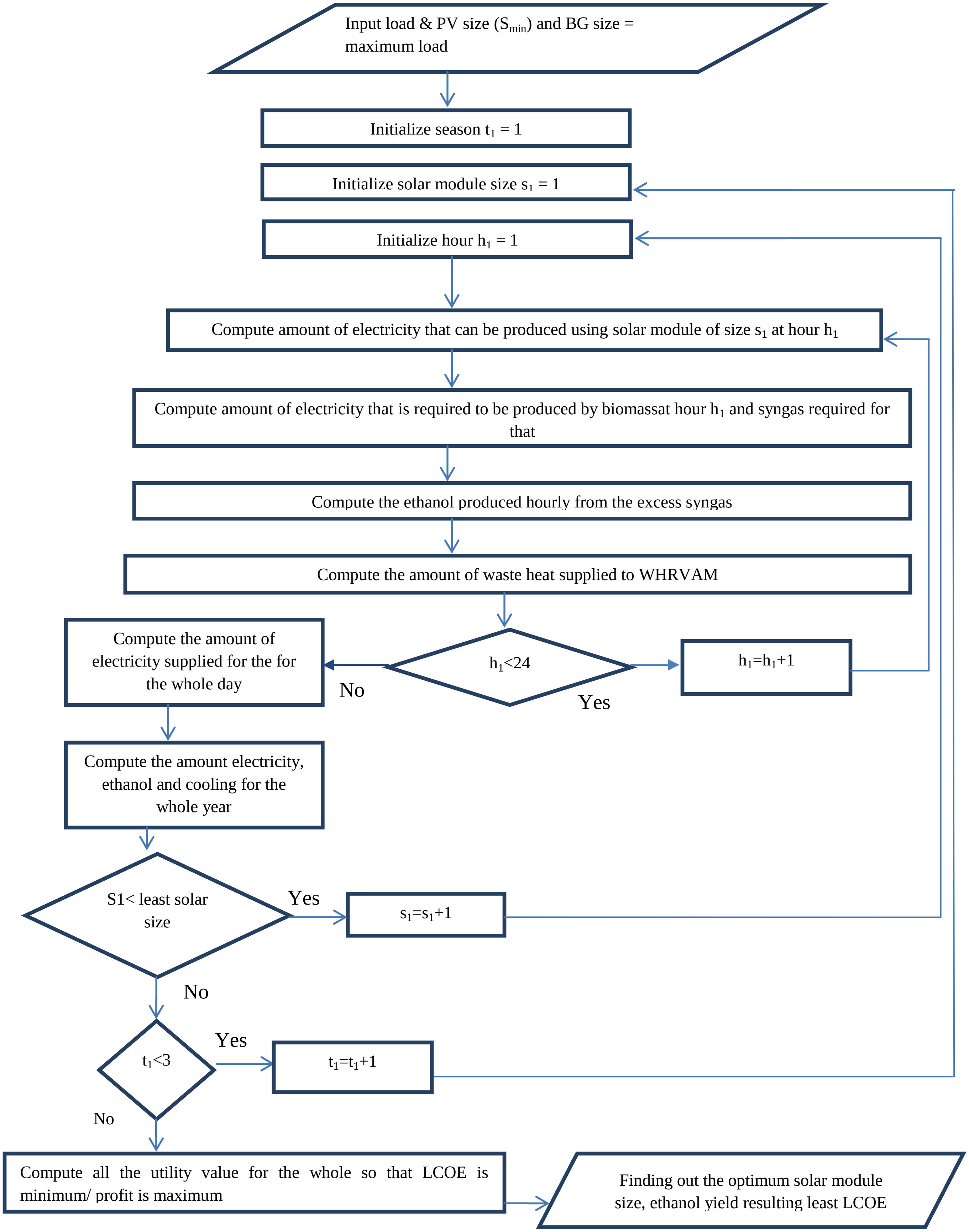

Figure 3.3(b): Flow chart for determination of optimum size of solar module, gasifier and ethanol producing units

3.2.3.4.1. Capital Recovery Factor (CRF)

A capital recovery factor is a function of the bank discount rate and life of the plant and is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time as shown in Eqn.3.13 (National Renewable Energy Laboratory).

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.13}$$

Where i is the bank discount rate and n is the life of the plant in years.

3.2.3.4.2. Annualized cost

For renewable energy systems, the initial investment is much higher than the running cost per year. So the annualized cost/ equal annual installment of these systems are given by the product of the net present value (NPV) of the system and the capital recovery factor (CRF) as follows (National Renewable Energy Laboratory).

$$AC = NPV \times CRF \tag{3.14}$$

The annualized cost of solar module $C_{PV_{module}}$ is given by

$$C_{PV_{module}} = S_{cap} \times S_{pw} \times CRF \tag{3.15}$$

where S_{cap} is the capacity of solar module and S_{pw} is the cost of solar module per watt-peak.

The annualized cost of biomass gasifier C_{BG} is given by

$$C_{BG} = C_{eqb} \times CRF \tag{3.16}$$

where,C_{eqb} is the cost of biomass gasifier of required size.

The annualized cost of ethanol synthesis unit C_{ethsyn} is given by

$$C_{ethsyn} = TC_{esyn} \times CRF \tag{3.17}$$

where,TC_{esyn} is the total cost of ethanol synthesis unit of required size.

The annualized cost of ethanol separation unit is given by$C_{ethsep} = TC_{esep} \times CRF$ (3.18)

where,$TC_{esep}$is the total cost of ethanol separation unit of required size.

The annualized cost of waste heat recovery vapor absorption cooling systemis given by

$$C_{vam} = TC_{WHRVAM} \times CRF \tag{3.19}$$

The annualized cost of the solar inverter

$$C_{inv} = In_{cap} \times In_{pp} \tag{3.20}$$

Here, In_{cap} is the capacity of solar inverter and In_{pp} is the price per watt peak of solar inverter.

The annual cost of purchasing straw C_{Straw} is $C_{Straw} = S_{in} \times 365 \times SC_{perkg}$ (3.21)

where,SC_{perkg} is the cost of straw per kg.

The cost of catalyst per annumC_{Mos_2}

$$C_{Mos_2} = C_y \times C_{ckg} \tag{3.22}$$

Where C_{ckg} is the cost of MoS_2 catalyst per kg.

3.2.3.4.3 .Annualized expenditure

Annualized expenditure (AE) includes the annualized initial investments of the renewable energy systems and the annual cost incurred to procure the consumables needed to run the system.

$$AE = C_{Mos_2} + C_{Straw} + C_{PV_{module}} + C_{BG} + C_{ethsyn} + C_{ethsep} + C_{vam} + C_{inv} + C_{ge} + M_c \tag{3.23}$$

Where $C_{Mos_2}$is the cost of catalyst per annum, $C_{Straw}$is the annual cost of purchasing straw, is $C_{PV_{module}}$the annualised cost of solar PV module,$C_{BG}$is the annualised cost of biomass gasifier $C_{ethsyn}$is the annualized cost of ethanol synthesis unit, $C_{ethsep}$is the annualised cost of ethanol separation unit, C_{vam} is the annualised cost of waste heat recovery vapor absorption cooling system,C_{inv} is the annualized cost of the solar inverter, C_{ge} is the annualized cost of gas engine and $M_c$is the maintenance cost of the system.

3.2.3.4.4.Annualized Income

The annualized income (AI) is the total revenue earned from this system by selling output utilities, i.e., electricity, ethanol and providing cooling utility.

$$AI = \left(E_{year} \times T\right) + E_R + C_R \qquad (3.24)$$

$E_{year}$is the total units of electricity generated per annum,T is the electricity tariff, $E_R$is the yearly revenue earned by selling ethanol and $C_R$is the yearly revenue earned by providing cooling utility.

3.2.3.4.5. Annualized profit (AP)

The difference between the annualized income (AI) and annualized expenditure (AE) gives the annualized profit (AP) whose maximization is the objective function for this study.

$$AP = AI - AE \qquad (3.25)$$

3.2.3.4.6. Optimized profit (OP)

The optimized profit is the objective function here which is maximized under certain boundary conditions like meeting the load demand at all the hours of the day with good reliability keeping in phase with the intermittent availability of local resources like straw and solar energy.

$$OP = maximum(AP) \qquad (3.26)$$

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3.2.3.4.7. Payback period (PBP)

The simple PBP is calculated as follows

$$PBP = \frac{AE}{CRF \times AS} \qquad (3.27)$$

Where AS is the annualized savings.

3.2.3.4.8. Levelized Cost of Electricity

The LCOE is given by $LCOE = \frac{\sum_{t=1}^{n} I_t + M_c + F_t}{\sum_{t=1}^{n} E_t} \times (1 + r)^n$ (3.28) where I_t is the investment expenditures in year t, $M_c$is the operation expenditures in year t, F_t is the fuel expenditure in year t, E_t is the electricity generated in year t, r is the discount rate and n is the economic life of the system.

3.2.3.4.9.Optimization variables

The objective function of this optimization problem is maximization of annualized profit (AP). This objective is dependent on several variables as shown in Eqn. 3.29.

$$AP = f\left(C_{Mos_2}, C_{Straw}, C_{pv\,module}, C_{BG}, C_{ethsyn}, C_{ethsep}, C_{vam}, C_{inv}, C_{ge}, M_c, E_{year}, T, E_R, C_R, n, i\right) \quad (3.29)$$

The various constraints of optimization are

$$P_r = 100\% \quad (3.30)$$

$SD_{max} \leq 4.8\ kt/y$ (Indian Institute of Science, Biomass Resource Atlas of India) (3.31)

$$P_{biomass} \geq 0.5\ kW \quad (3.32)$$

$$WH_{min} = 15\ kW \quad (3.33)$$

$$PV_{max} = 6\ kW \quad (3.34)$$

where,P_r is the reliability of power supply and calculated as shown in Eqn. 3.30 and SD_{max} is the maximum yearly straw demand. The maximum straw demand for electricity generation and ethanol production should not exceed the maximum excess straw availability of the Sunderban area. The maximum straw availability is obtained from Biomass Resource Atlas of India as given in (Indian Institute of Science, Biomass Resource Atlas of India). The minimum amount of the biomass power ($P_{biomass}$) has to be generated to produce the necessary waste heat to run vapor absorption cooling system. The maximum size of the solar module (PV_{max}) is chosen in such a way that in all the instances of the day there is a generation of power by the biomass-gas engine system which is greater or equal to P_{bioh}. The capacity of the solar module is varied up to

$PV_{max}$for the optimization problem in the present study. The efficiency of the PV module and COP of the vapor absorption system are constraints whose values are given in Table 3.2.

The annualized profit (AP) as shown in Eqn. 3.25 and Eqn. 3.29 is the dependent variable. The independent variables are annualized cost of MoS_2 catalyst (C_{Mos_2}), annualized cost of straw (C_{Straw}), annualized cost of solar module ($C_{pv\,module}$), annualized cost of gasifier (C_{BG}), annualized cost of ethanol synthesis unit (C_{ethsyn}), annualized cost of ethanol separation unit (C_{ethsep}), annualized cost of waste heat recovery vapor absorption cooling system (C_{vam}), annualized cost of inverter (C_{inv}), annualized cost of gas engine (C_{ge}), annual maintenance cost (M_c), unit cost of electricity (T),annual revenue from ethanol selling(E_R), revenue from cooling utility (C_R) , life of the plant (n) and the bank discount rate (i). This annualized cost depends on the capacity of each of the system components. In this chapter optimization is carried out from economic point of view to choose the best from a given range of numbers.

3.2.3.5. Reliability analysis

Here the variation of the profit against the reliability of the system is carried out for three different cases, say, (i) designing the system to cater only the least load i.e. when the chance of power failure is highest (ii) designing the system to cater the average load i.e. the chance of power failure is moderate and (iii) designing the system to cater the highest load i.e. the chance of power failure tends to zero. The reliability analysis is done by using the loss of power supply probability (LPSP) and unmet load (UL) probability method (Sinha and Chandel, 2015).In the LPSP method, both the time of power failure and the magnitude of the power deficit are considered whereas in UL method only the total time of power failure is considered.

$$LPSP = \frac{\sum_{i=1}^{i=n} E_{deficit}}{\sum_{i=1}^{i=n} P_{load}} \times 100 \tag{3.35}$$

where$E_{deficit}$ is the total electrical energy deficit over a year and P_{load} is the total electrical energy required per year.

$$UL = \frac{\sum_{i=1}^{i=n} P_{failure}}{\sum_{i=1}^{i=n} P_{total}} \tag{3.36}$$

$P_{failure}$is the total time when there is electricity deficit and P_{total} is the total hours of operation of the plant.

3.2.3.6. Emission Reduction

The life cycle emission factors of diesel generator, solar photovoltaic panel and biomass gasifier are given in later section. The percentage of CO_2 emission reduction, for the proposed polygeneration unit compared to power generation by diesel generator (DG) sets practiced presently is calculated as

$$E_{RR} = \frac{(E_{DG} \times E_{year}) - (E_{solar} \times El_{solar}) - (E_{bio} \times El_{bio}) \times 100}{(E_{DG} \times E_{year})} \tag{3.37}$$

Where E_{RR} is the percentage of emission of CO_2 reduction per year is, E_{solar} (98 g-CO_2/kWh (Akella et al., 2009)) is the CO_2 emission by solar module per kWh electricity produced, El_{solar} is the total units of electricity generated by the PV module per year, E_{bio} (17 g-CO_2/kWh (Akella et al., 2009)) is the CO_2 emission of biomass gasifier per kWh electricity produced, El_{bio} is the total units of electricity generated by the biomass gasifier per year, E_{DG} (742.1 g-CO_2/kWh(Akella et al., 2009)) is the CO_2 emission of DG set per kWh electricity produced and E_{year} is the total units of electricity generated per year.

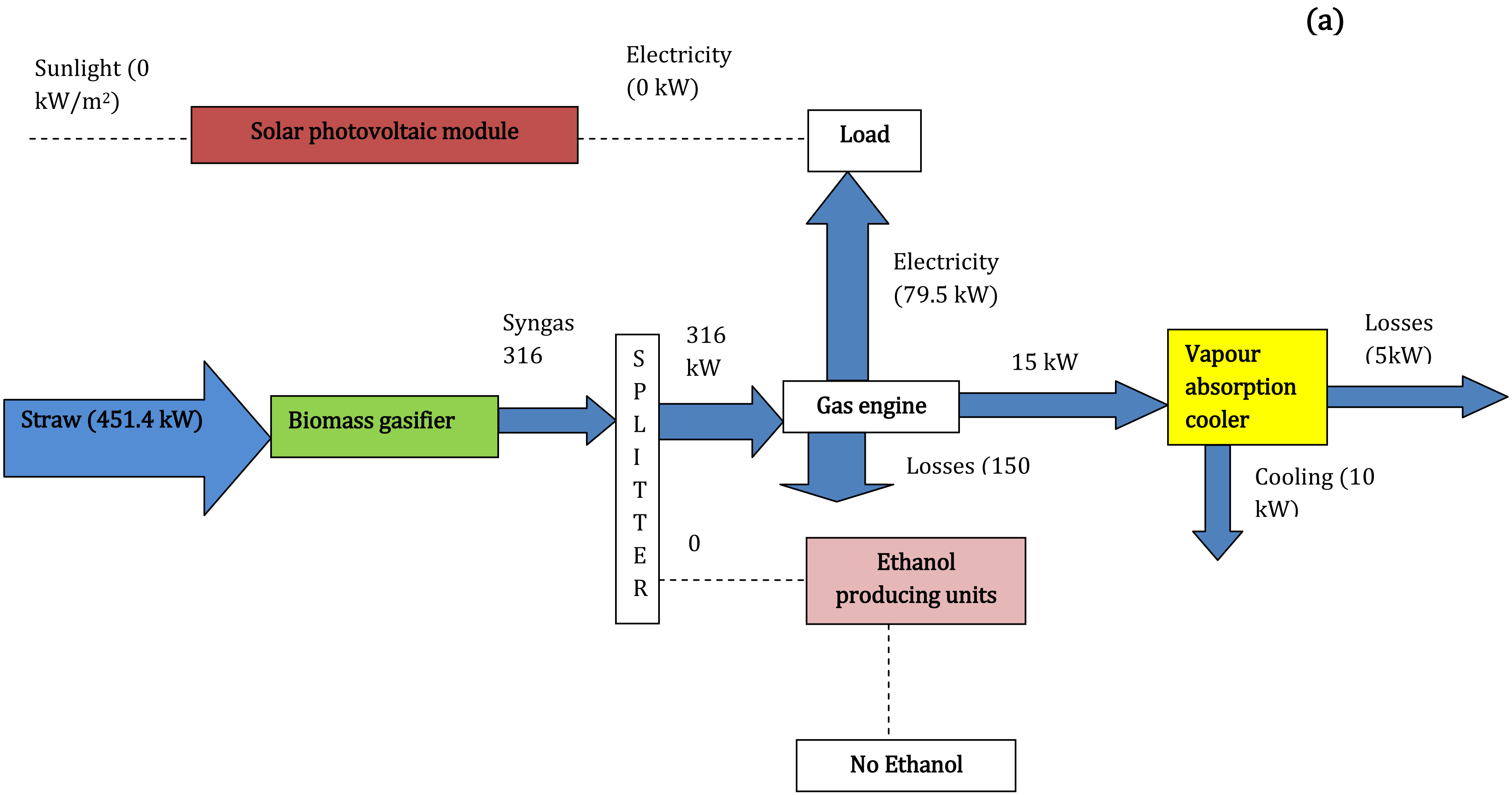
3.3. Results and discussion

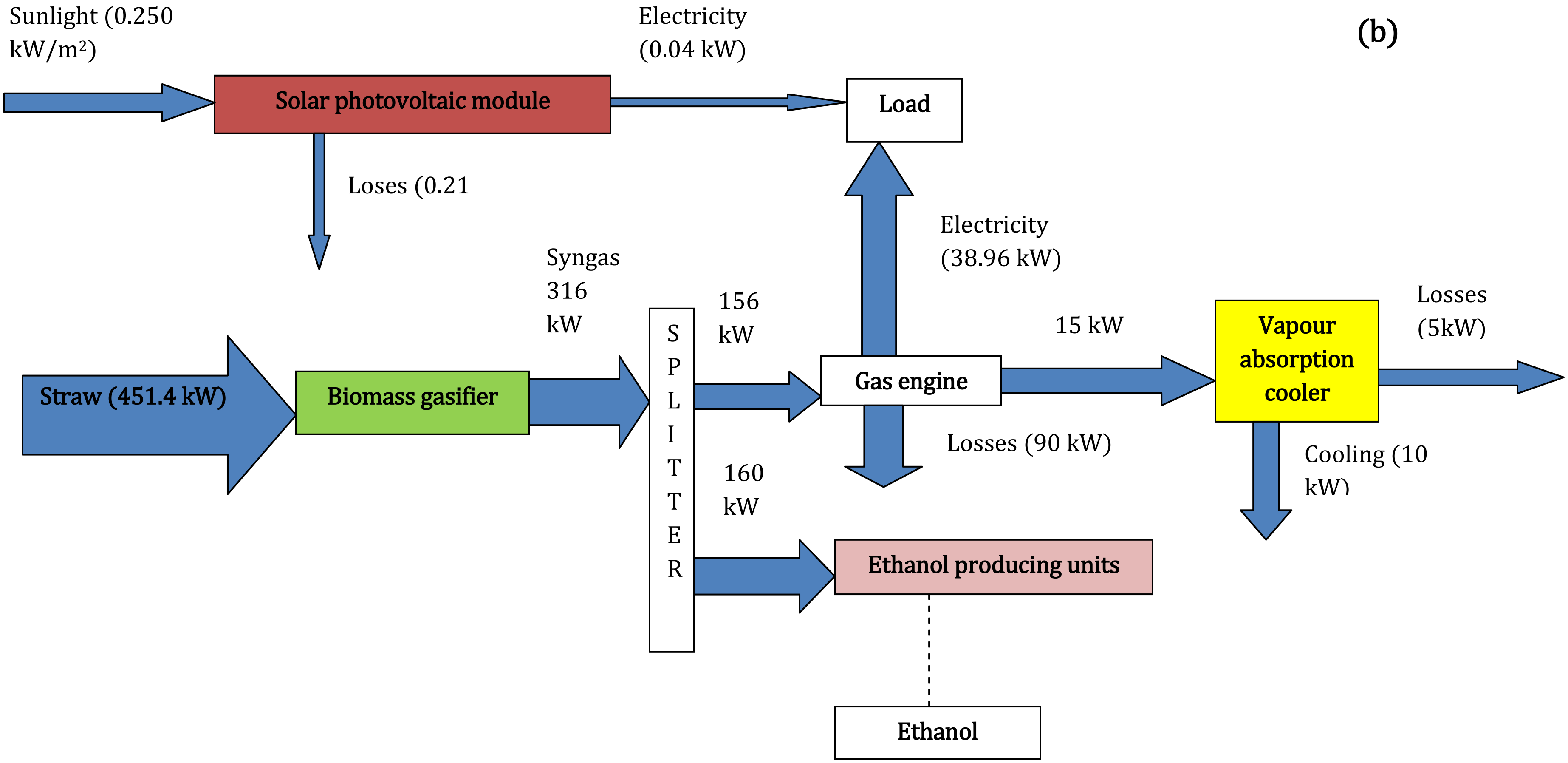
In this chapter, the size of the various components of the polygenration system as shown in Figure3.1 is determined using linear programming with MATLAB. The thermodynamic optimization data are taken from a paper of the same group (Jana and De, 2015). In the present work economic optimization is carried out without compromising with the reliability of the power supply. This study determines the optimum size of the components and the amount of reduction in carbon emission as a result of this hybrid polygeneration which is shown in Table 3.3.

Table 3.3: Optimized results of the system design

Serial No	Parameter	Value
1	Electrical output of biomass-gas engine	79.85 kWe
2	Capacity of Solar PV module	1 kW
3	Size of the vapor absorption chiller	3 tone of refrigeration
4	Yearly ethanol production	1619.3 liters
5	Simple payback period	2.5 years
6	Reduction in CO_2 emission with respect to diesel generator set	96%
7	Return on Investment	13.5%
8	Net Present Value	480000 million INR
9	Internal Rate of Return	10.6%

The size of the biomass gasifier must be corresponding to the maximum load. The maximum load occurs during the evening time when there is no solar insolation. So the total power at that instant has to be met by the biomass power only. The Sankey diagram of the system for maximum load, medium load and the minimum load in a year is shown in Figures3.4(a-c). The ethanol production is zero at the time of maximum load. The maximum load occurs at the evening time when there is no solar energy. Hence the entire load has to be caters by the biomass power. Thus the power from the individual sources at the three instances i.e. maximum load, medium load and least load are also shown in Figures 3.4 (a-c).


(a)
Sunlight (0 kW/m²)
Solar photovoltaic module
Electricity (0 kW)
Load
Electricity (79.5 kW)
Syngas 316
316 kW
SPLITTER
Straw (451.4 kW)
Biomass gasifier
Gas engine
15 kW
Vapour absorption cooler
Losses (5kW)
Losses (150
Cooling (10 kW)
0
Ethanol producing units
No Ethanol

Sunlight (0.250 kW/m²)
Solar photovoltaic module
Electricity (0.04 kW)
Load
(b)
Loses (0.21
Electricity (38.96 kW)
Syngas 316 kW
156 kW
15 kW
Losses (5kW)
Vapour absorption cooler
Straw (451.4 kW)
Biomass gasifier
SPLITTER
Gas engine
Losses (90 kW)
Cooling (10 kW)
160 kW
Ethanol producing units
Ethanol

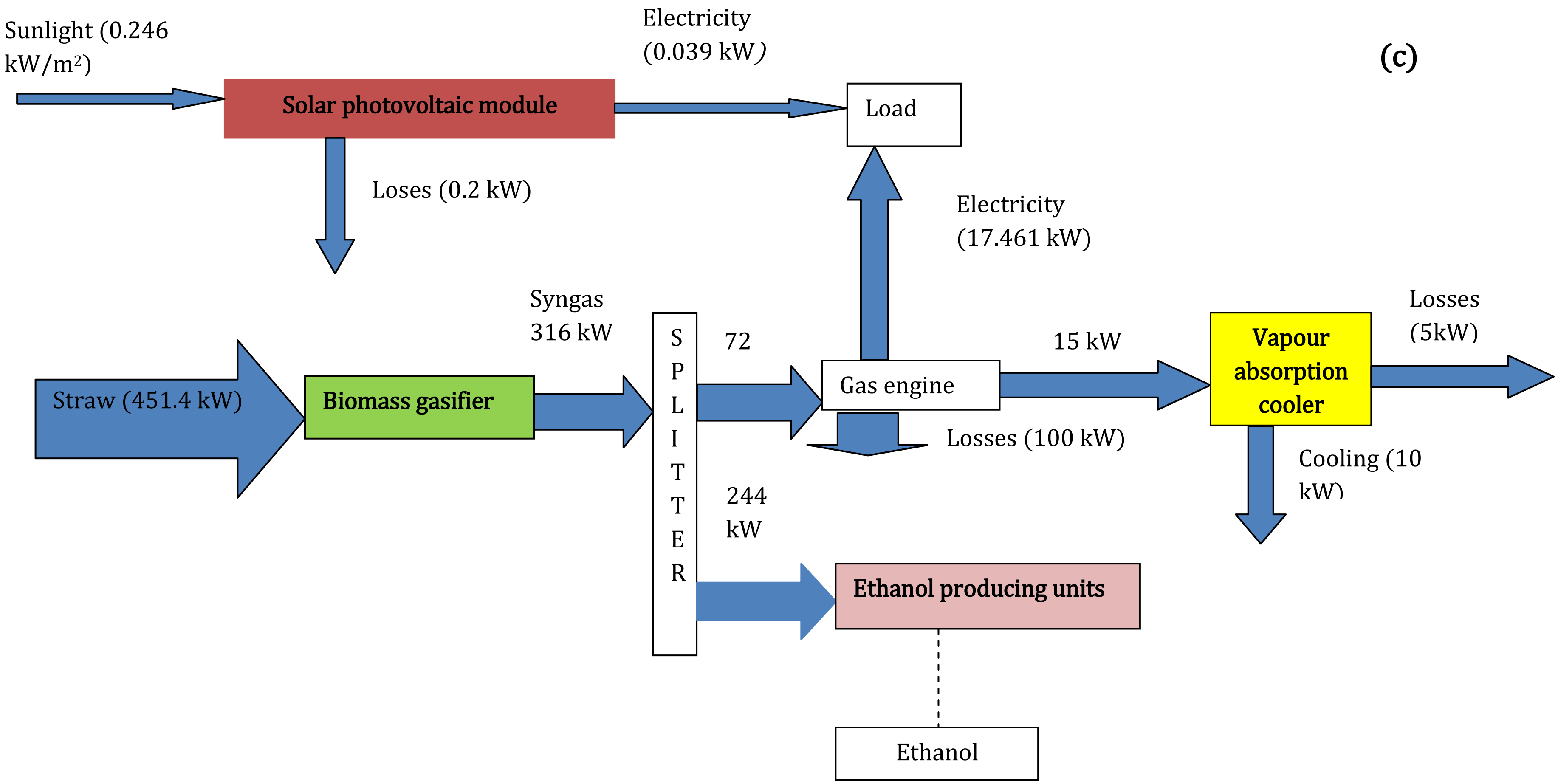


Figure3.4: Sankey diagram of polygeneration plant (a) for highest electrical load (b) medium electrical load (c) least electrical load

3.3.1. Sensitivity analysis

Sensitivity analysis is essential to assess the performance or viability of the system with the economic parameters. It helps to identify parameters for the better performance of the plant. The net profit depends on several operating and economic parameters.

Figure3.5 (a) shows the variation of profit with varying hours of failure and the probability of loss of power supply.

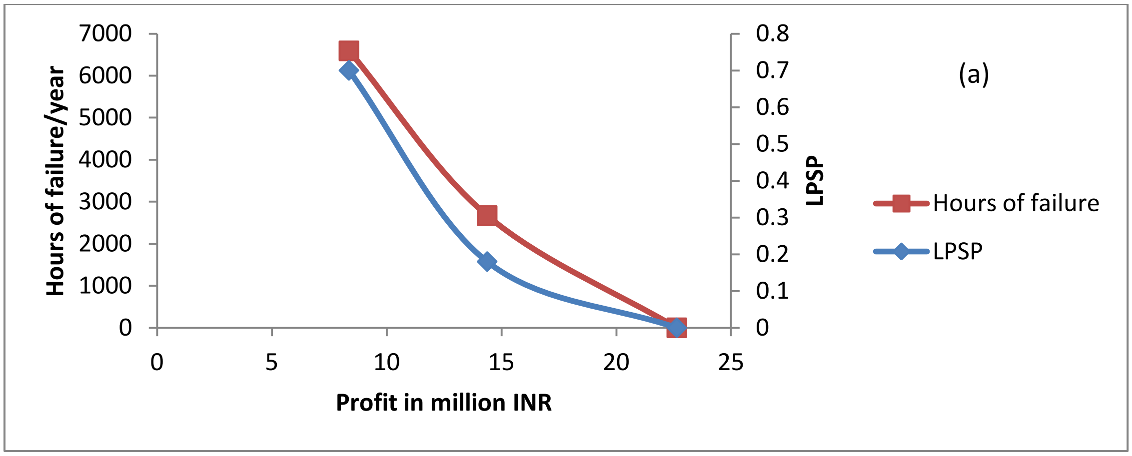


Figure 3.5(a): Variation of Profit with the hours of failure and LPSP

The profit has decreased with the increase in the hours of failure though the initial capital investment decreases with the decrease in reliability. Thus the profit is maximum when the chance of power failure tends to zero. This is socially a better solution also even with the best economic performance. As expected, Loss of power supply probability (LPSP) also shows similar trend with hours of failure per year. This is because the installation cost of the renewable energy systems is very high as compared to operation and maintenance cost. During the hours of failure the system is unable to generate any revenue. Hence profit lowers if hours of failure increase.

Figure3.5(b) shows the variation of profit with varying cost of straw. The profit linearly decreases with the increase in the cost of straw. But when the cost of the straw becomes greater than 12 INR/kg then the optimized solar module size increases to 5 kW from 1 kW. As a result, the percentage of solar power in the mix of biomass and solar power in the local micro grid increases. There is a parallel shift in the curve when the cost of straw increases above 12 INR/kg.

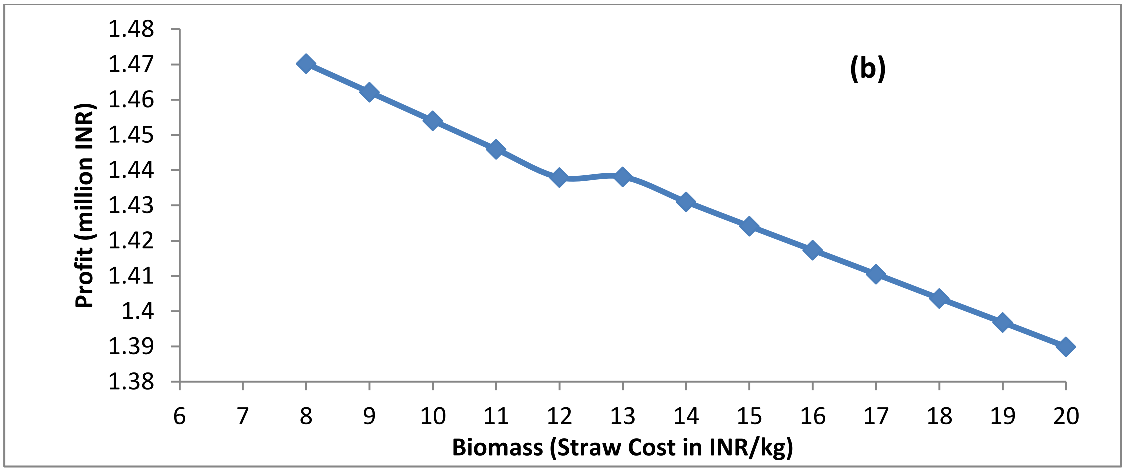


Figure 3.5(b): Variation of Profit with cost of straw

Figure3.5(c) shows the variation of profit with varying cost of solar module.

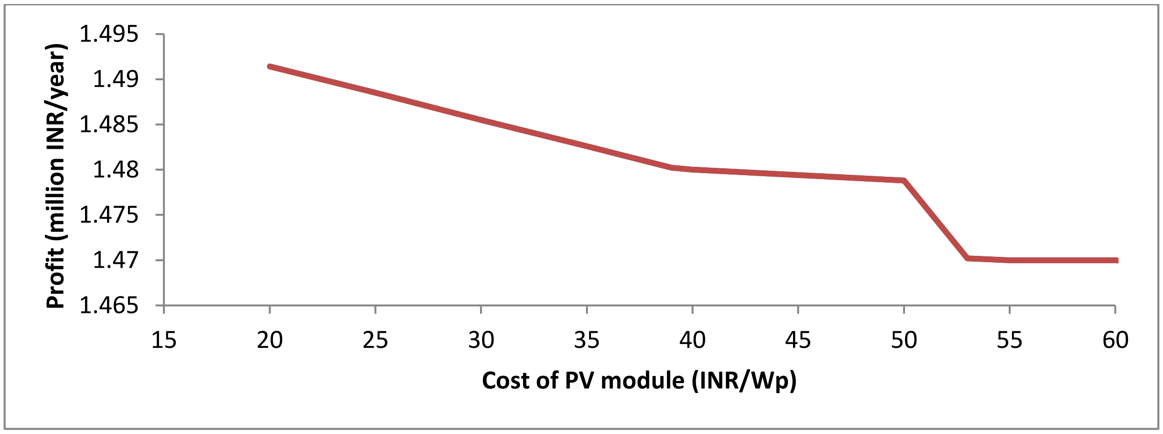


Figure 3.5(c): Variation of Profit with cost of solar module

Since 1998, the price of the photovoltaic systems has fallen by 6% to 8% yearly on an average (Term et al., 2014). From 2012, onwards the price of the systems of less than 10kW has fallen by 12% and by 15% for systems which are more than 100 kW. So a sensitivity analysis is carried out varying the price of the solar modules to see the effect. If the price of the solar module falls below 40 INR/Wp then the optimized size of the solar module changes to 5 kW from 1kW. For the present study the levelized cost of electricity also increases with the increase in the percentage of solar power in the mix of solar and biomass power in the local micro grid. The sharp fall in the curve indicates the share of increase in the solar power in the power mix. As the capacity of solar module increases there is a sharp fall in the curve. The profit varies in the same rate with the variation of the electricity tariff as shown in Figure 3.5(d).

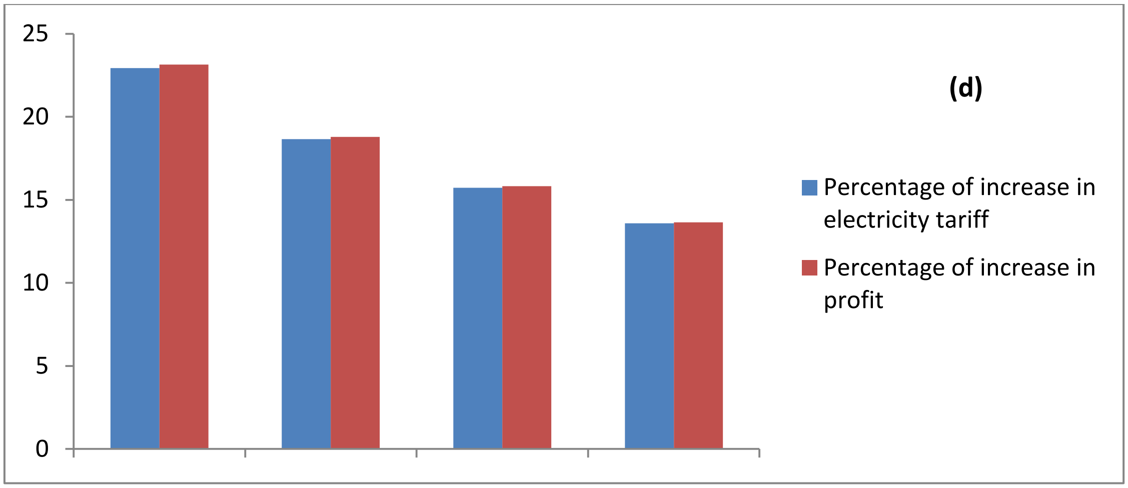


Figure 3.5(d): Variation of Profit with electricity tariff

Unlike electricity tariff, the profit does not increase similarly with the increase in the ethanol price as shown in Figure3.5 (e).

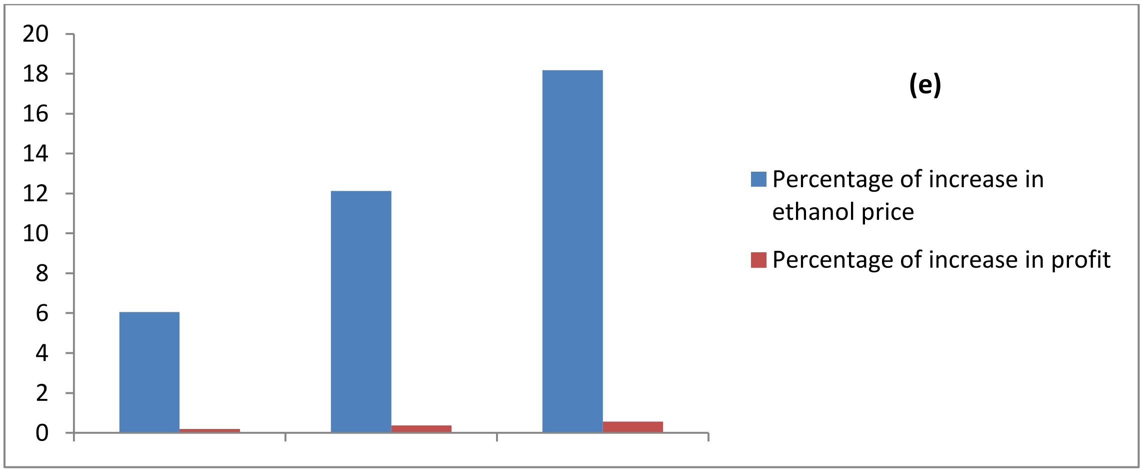


Figure 3.5(e): Variation of Profit with price of ethanol

This is because the biomass power has the maximum share in the power mix of this system as maximum load occurs during the evening time. Hence, a small amount of syngas is left over for ethanol synthesis. Yearly production of ethanol is relatively small. Hence the variation of ethanol price has comparatively less effect on the net profit.

The profit increases sharply with the initial increase of life of the plant as shown in Figure 3.5(f).

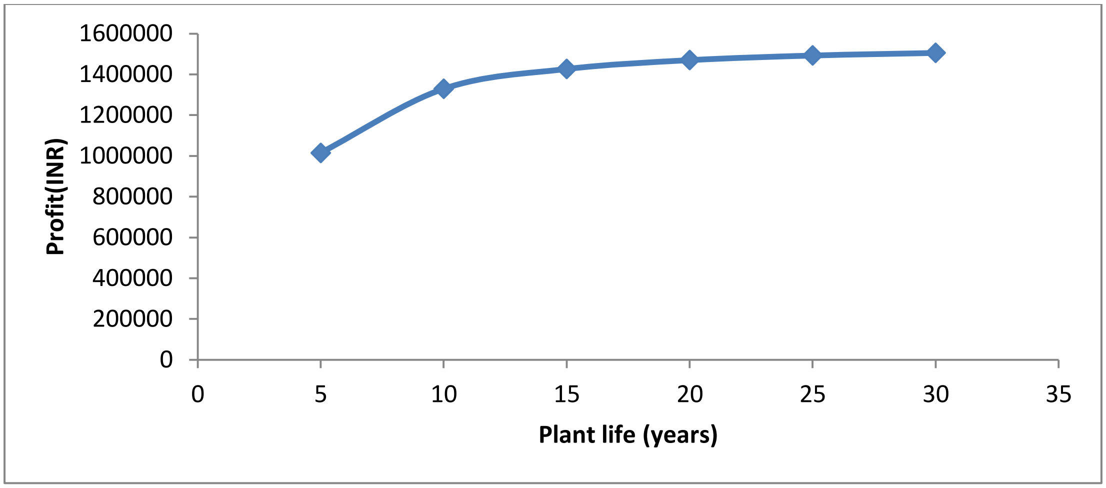


Figure 3.5(f): Variation of Profit with life of the plant

Alternately, there is a sharp decrease in the profit if the plant life is below a minimum value, say, 10 years. However, this effect does not exist beyond certain value of the plant life, say, 25 years, i.e., the net profit has insignificant sensitivity on the plant life beyond this value.

Figure3.6 shows the variation of the LCOE with hybridization as well as process integration.

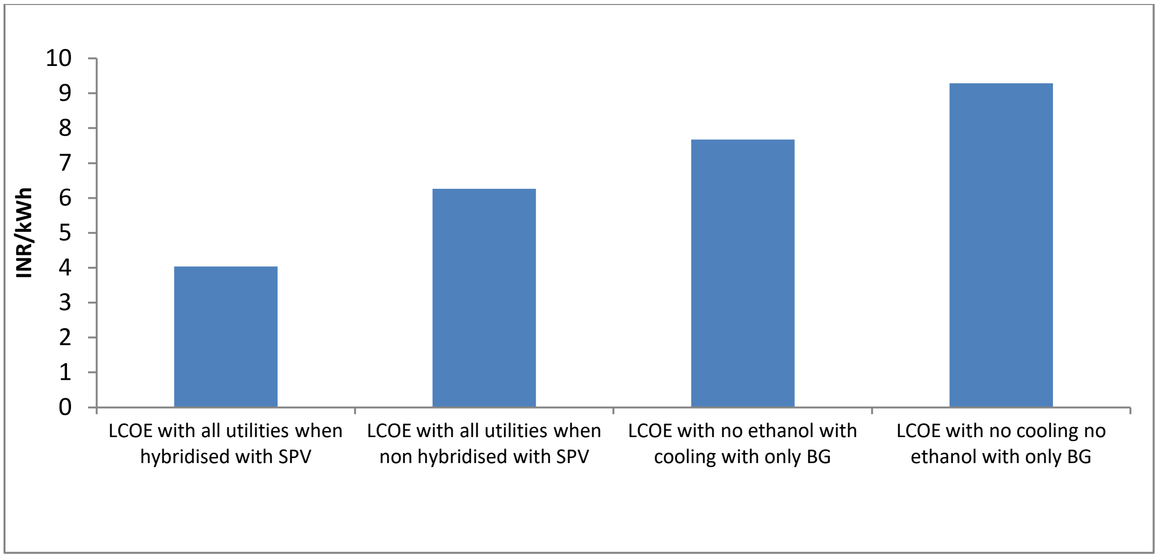
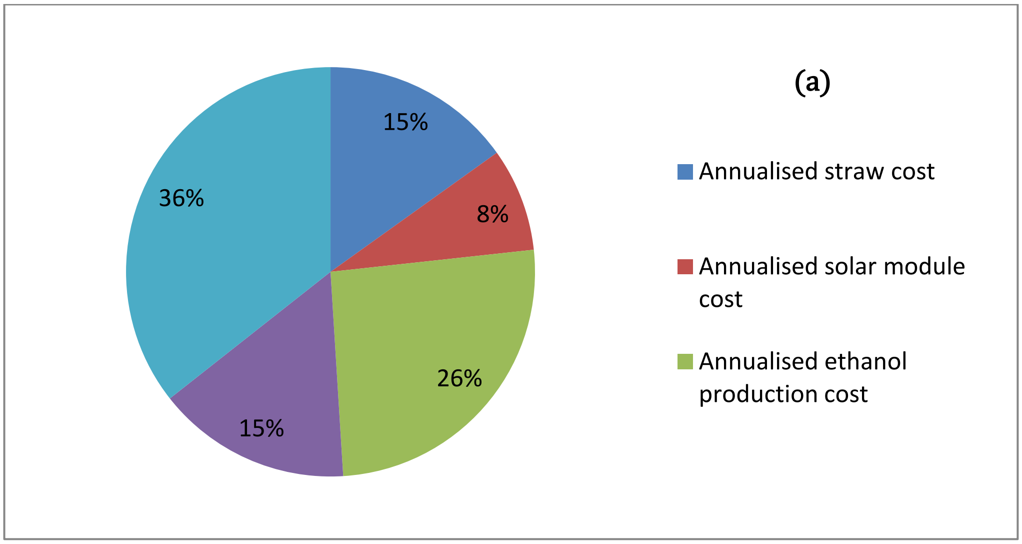


Figure3.6: Variation of LCOE with hybridization and adding up of utilities

It shows the variation of the LCOE with hybridization as well as process integration. The result shows that with hybridization the LCOE decreases. There is a significant decrease of LCOE as a result of adding up of utilities like ethanol and cooling.

Figure3.7(a-b) shows the annual expenditure and income shares of the polygeneration plant.



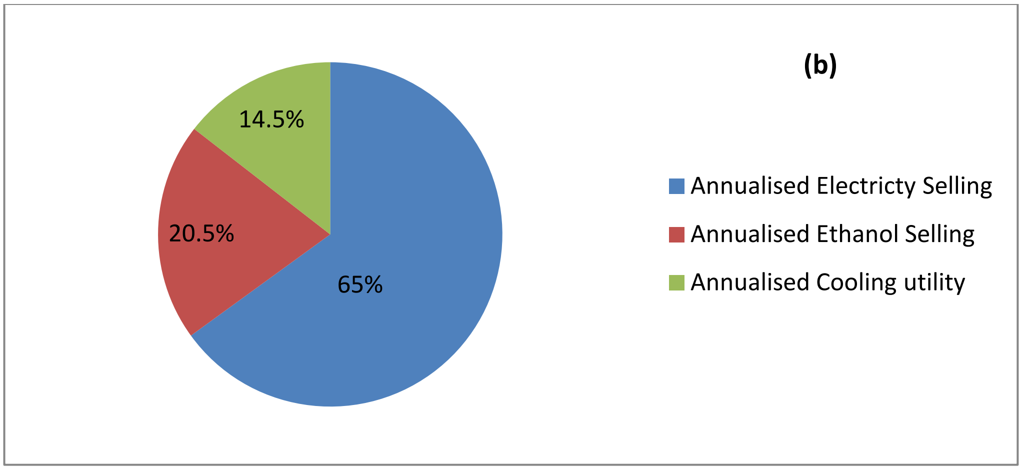
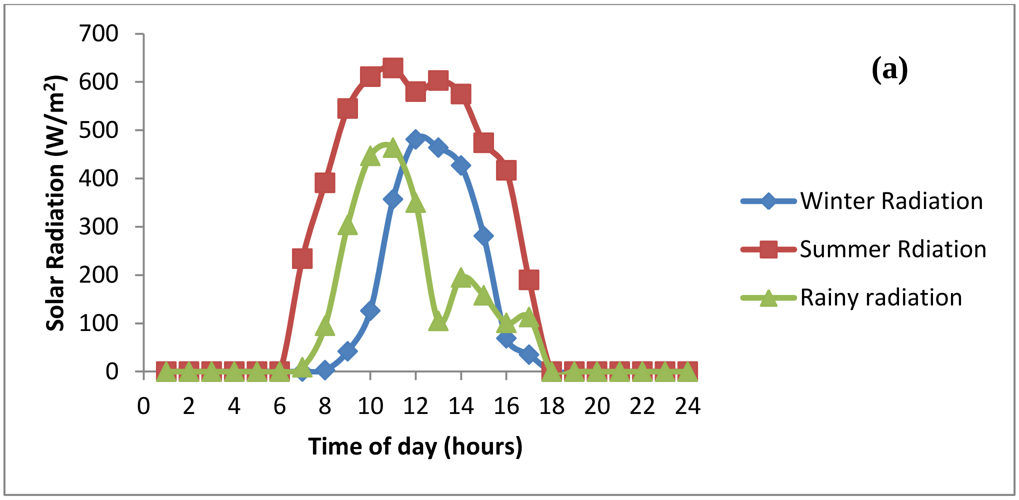


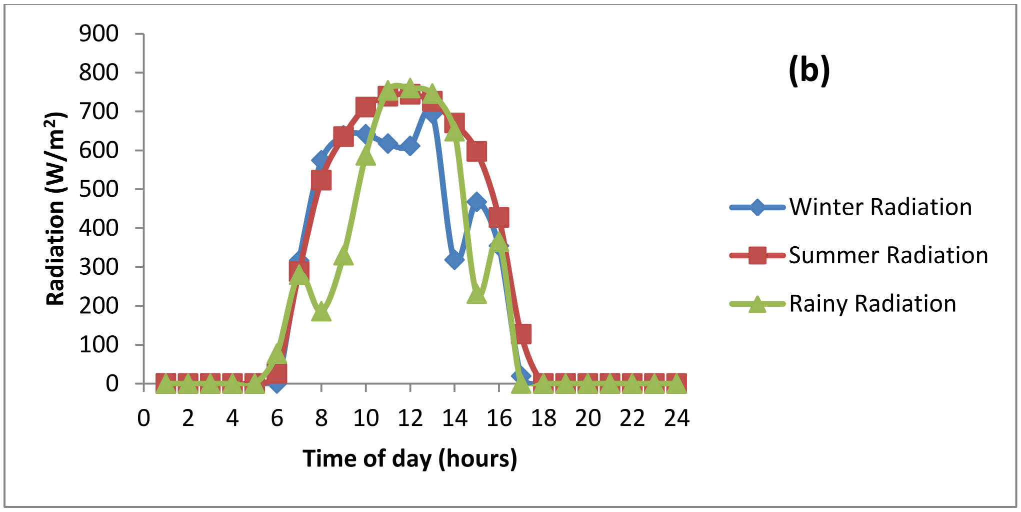
Figure 3.7: Pie chart for (a) annualized expenditure share (b) annualized income share

The annualized cost of the biomass gasifier takes maximum share in the total annualized expenditure. This is because major portion of the electricity (main utility output) is coming from biomass gasifier. Moreover the syngas produced by the biomass gasifier is also used for the ethanol production. The waste heat of the gas engine is used to run the vapour absorption cooling system. The gasification unit has a contribution in some way in all the utilities. The solar module cost in the annualized expenditure share is less (~15%) as solar contributes much less to the electricity generation than biomass. The installation of solar module enhances the ethanol production as the syngas used in the gas engine for electricity production reduces as a result.

3.3.2. Scenario analysis

This work is aimed at using the local resources for producing electricity with some other utilities. India is a vast country with six climatic zones (Climatic zones and their characteristics). So the availability of local resources also varies with geographic location. India has eleven solar zones with a wide variation of the magnitude of solar radiation (Gupta, 2014). The performance of the proposed system will vary with the variation of solar radiation. So it is expected that the optimum performance will vary with the location. Hence, a scenario analysis for three different cities in other three different parts of India is also carried out. The study is thus carried out for four different places located in eastern (Sunderban, place of study), northern (Delhi), southern (Chennai) and western (Ahmedabad) part of India for comparing the effects of location only. The seasonal variations of the solar insolation in the three places (Ahmedabad, Delhi and Chennai) are shown in Figures3.8 (a), b, and c.





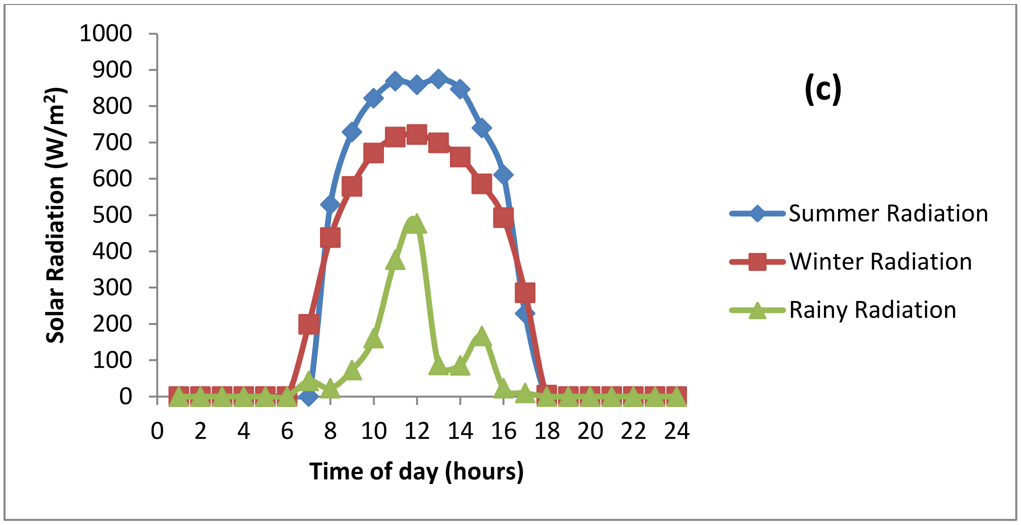


Figure 3.8: Seasonal variation of Solar Insolation at (a) Delhi (Northern India) (b) Chennai (Southern India) (c) Ahmedabad (Western India)

This hybrid system delivers electricity according to local load curve and a constant cooling load. Electricity is delivered either through solar PV or biomass gas engine system. Thus gas engine compensates the gap between electricity demand and supply of that by solar PV. However, gas engine exhaust is used as source of waste heat for running the WHRVAM. Thus to run the WHRVAM, gas engine minimum size is constrained by the constant cooling load. Also, gasifier capacity being fixed, excess syngas produced above the gas engine input is used for ethanol production that also contributes to the levelized cost of electricity. Solar radiation being lower in Sunderban and Chennai areas, gas engine capacity has to be higher to meet the electricity demand. Automatically available waste heat for running of the WHRVAM is sufficient. On the other hand, in spite of higher solar radiation in Delhi and Ahmedabad, gas engine size cannot be reduced than a minimum capacity to meet the waste heat requirement for the WHRVAM. As a result, the levelized cost of electricity for all four places does not vary significantly. As observed, four regions experience a significant variation in the magnitude of the solar radiation as shown in Figures3.8(a)-(c). The load curve is assumed to be same for all these regions. The LCOE shows no significant increment or decrement (as shown in Figure3.9) as the LCOE is obtained when the size of the solar module is 1kW for all conditions.

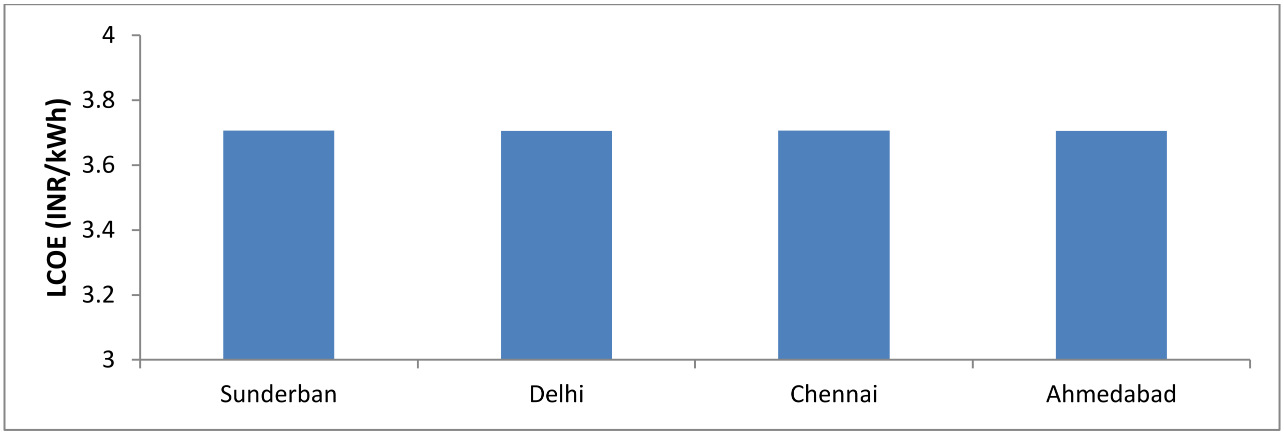


Figure 3.9: Levelized cost of electricity (LCOE) in four areas having different seasonal insolations

This is due to the following reasons: (i) in load curves, the maximum load is experienced during the evening in all the seasons. (ii) a minimum amount of biomass power has to be generated always because the vapour absorption cooling system runs on waste heat of the gas engine exhaust. For Sunderban and Chennai radiation situations, the maximum module size is 6kW where there is no shortage of waste heat supply from the gas engine to the WHRVAM but in Delhi and Ahmadabad as the available solar radiation is high the maximum size of the solar module is 2kW and still there is no shortage of waste heat supply from the gas engine to the WHRVAM.

3.4. Conclusion

Distributed generation is a possible option for off-grid villages. However, this energy system should be economically affordable also. This is possible when the system utilizes locally available energy resources in optimum way. This also helps to reduce CO_2 emission compared to fossil fuels. Apart from electricity, cooling and transportation fuels are other kinds of secondary energy demand of a village. These utility demands can be met through polygeneration. Due to varying demand of utilities throughout the day and season, size optimization with constraint resources is important. In this chapter, locally available biomass and solar energy are used as input energy resources to cater to the secondary energy needs of local people i.e., electricity, cooling and ethanol.

Results show that the biomass resources when hybridized with the solar photovoltaic system become more beneficial as ethanol (i.e., biofuel) is also obtained without compromising with the reliability of the power supply. Simple payback period of this system is 2.5 years. It reduces significant amount of CO_2 emission. The increase in the solar power mix in the micro grid increases the levelized cost of electricity under give n radiation conditions. However, the system is dominated by biomass-gas engine due to constant cooling load supply. Hence, solar radiation does not affect much the levelized cost of electricity. The system exhibits best economic performance when the reliability of the power supply is the maximum. Thus the polygeneration using local resources may be a sustainable energy solution to this region.

4. Polygeneration using renewable resources: Cost optimization using linear programming

4.1. Introduction

Sustainable development is an important goal of the modern world. To make the human development more sustainable, generation and distribution of clean energy is imperative. Presently, electricity from the large coal based thermal power plants through national grid is the major source of power in India. However, coal based thermal power plants emit most of greenhouse gases causing climate change. To achieve sustainable development goals and also meeting the growing energy demand, distributed generation (DG)from renewable resources may be a sustainable option (Singh and Parida, 2012).

Polygeneration is a DG system where some other utilities like chemicals, bio-fuels, chill, heating etc., are produced along with electricity to cater the needs of the local people. The multi-input and multi-output nature of the polygeneration systems make it more environment friendly and economically viable if local resources and local demand for utility are properly matched. For efficient integration of a polygeneration, optimization with suitable objective function is important. The use of optimization algorithms is critical for proper sizing of the components (supply side management) with proper resource utilization in an economic way (Serra et al, 2009). Optimization is also useful for the proper load dispatch accommodating the variation in the electricity consumption pattern of a particular group of consumers (Rong and Lahdelma, 2016). Polygeneration is generally beneficial from the economic and the environmental point of view (Kabalina et al, 2017). El-Emam and Dincer (2018) have shown that efficient process integration through polygeneration has increased the exergy efficiency of the polygeneration plant. It also reduces the primary energy consumption than the standalone systems with the same utility outputs (Gopisetty et al, 2017)**.** The polygeneration system has to be technically feasible, environmentally benign and socially acceptable. So for a combined best performance, optimization between these aspects is necessary (Sigarchin et al, 2018). The optimization of a polygeneration is thus a multi criteria problem. For optimum design of a polygeneration, linear programming methods as well as heuristic optimization algorithms like genetic algorithm, swarm and evolutionary algorithms are used as reported in literature (Rong and Su, 2017).

In this chapter, the design methodology of polygeneration using linear programming for a typically off grid Indian village located at a remote location is presented. Locally available resources are the inputs to this polygeneration system. The optimization is carried out with defined availability of the resources and for 100% reliable power supply as the constraints and the minimization of levelized cost of electricity (LCOE) as the objective function. The obtained results may be useful to the policy makers for finding out the possible areas of the introduction of such systems in Indian context.

4.2. Materials and methods

A renewable energy based hybrid polygeneration system has been optimized with the locally available resources like solar, straw (biomass) and wind. Electricity, ethanol and chill are the output utilities of this polygeneration. Electricity is fed to the local microgrid. Ethanol is used locally as a transportation fuel. The vapor absorption chiller is used to store food grains, vegetables etc., for a short period, saythree days. A code is developed in MATLAB 2013 and the optimization is carried out using linear programming approach.

4.2.1. System Description

The polygeneration system consists of a solar module, biomass gasifier, a wind turbine and ethanol synthesis and separation units as shown in **Figure4.1**.

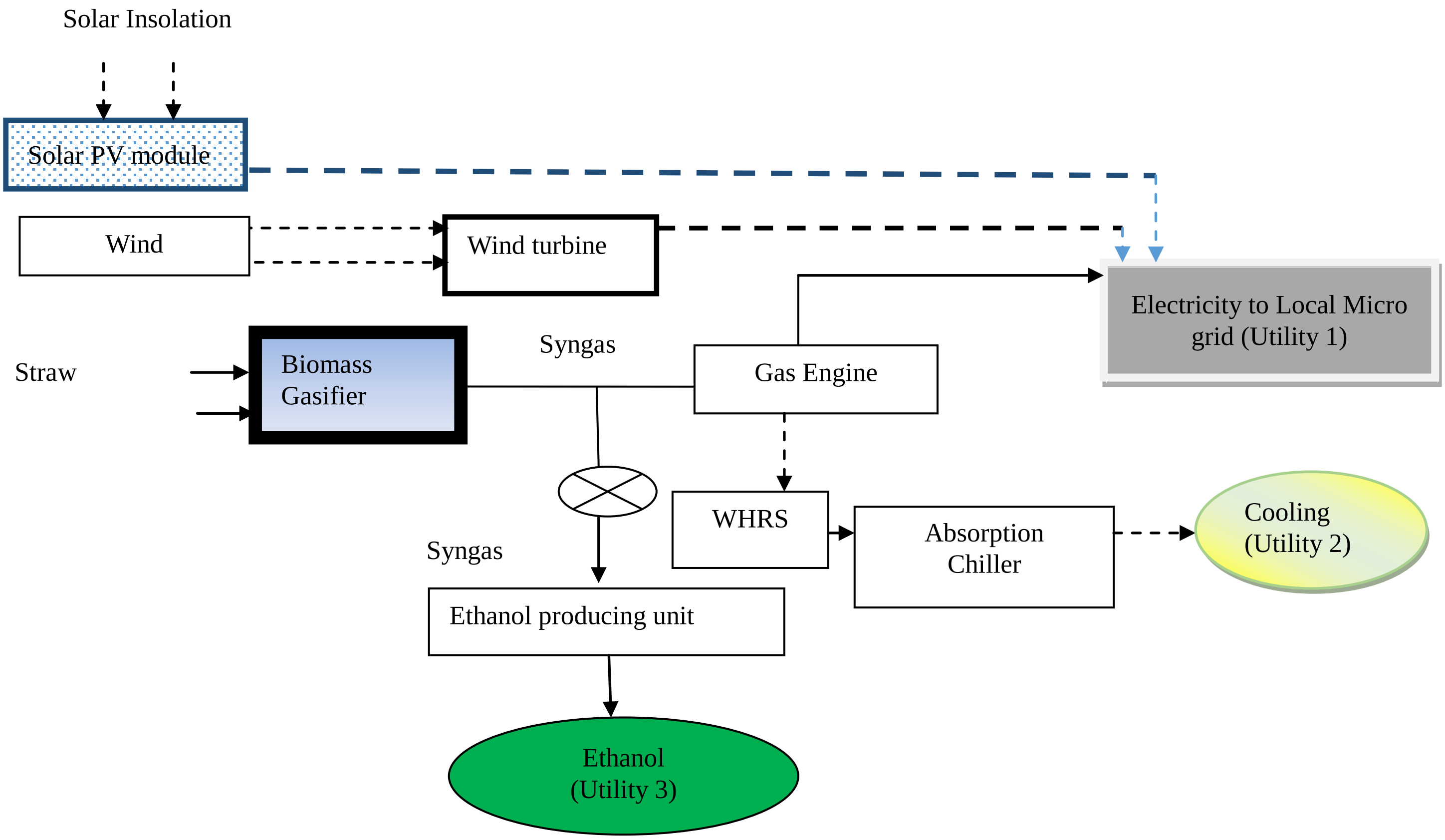


Figure4.1: Schematic of the polygeneration system

The solar radiation is incident on the solar module and it generates electricity. Straw is collected locally and is fed to the biomass gasifier. Syngas produced is fed to a gas engine to generate electricity. The gas engine is run in almost full load at most of the time. So change in efficiency of the gas engine has no significant effect on LCOE. The instantaneous load as shown in **Figure4.2** is met combinedly by the solar, biomass and wind power. When the load is low or the power generated by the wind turbine or solar module is relatively high then there is excess syngas which is not needed to generate electricity.

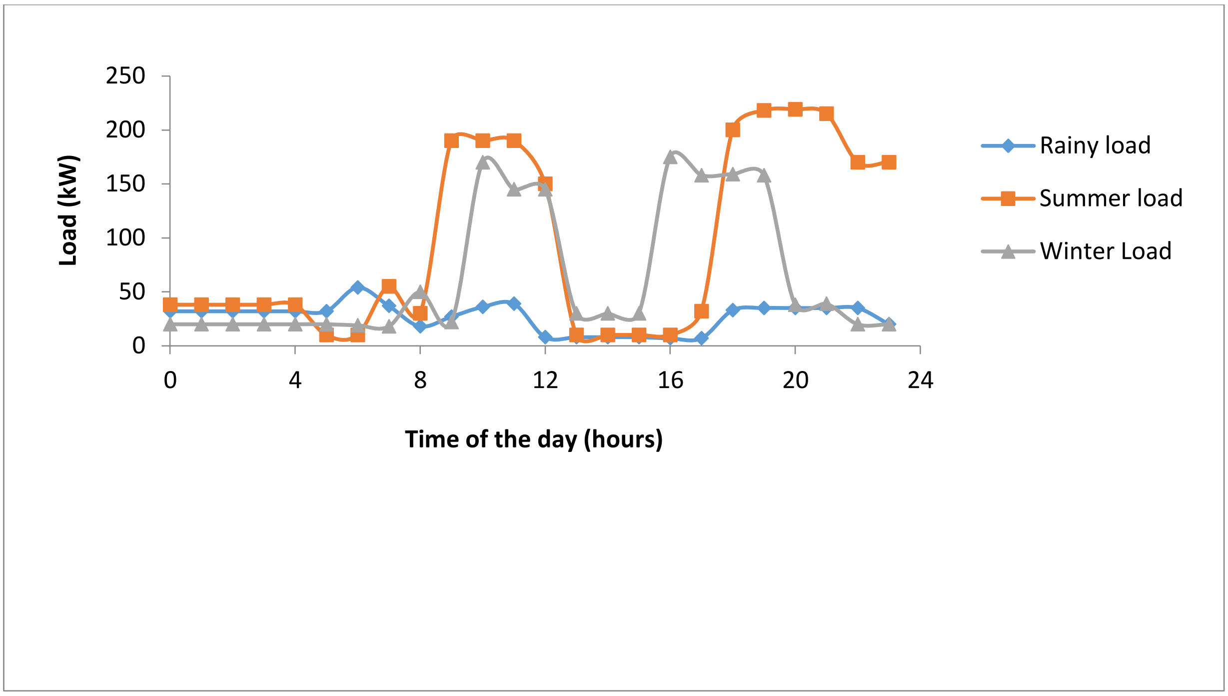


Figure4.2: Load curve for various seasons

The excess syngas is fed to the ethanol synthesis unit to produce ethanol with the help of MoS_2 catalyst following the water gas shift reaction. The solar radiation pattern is shown in **Figure4.3**.

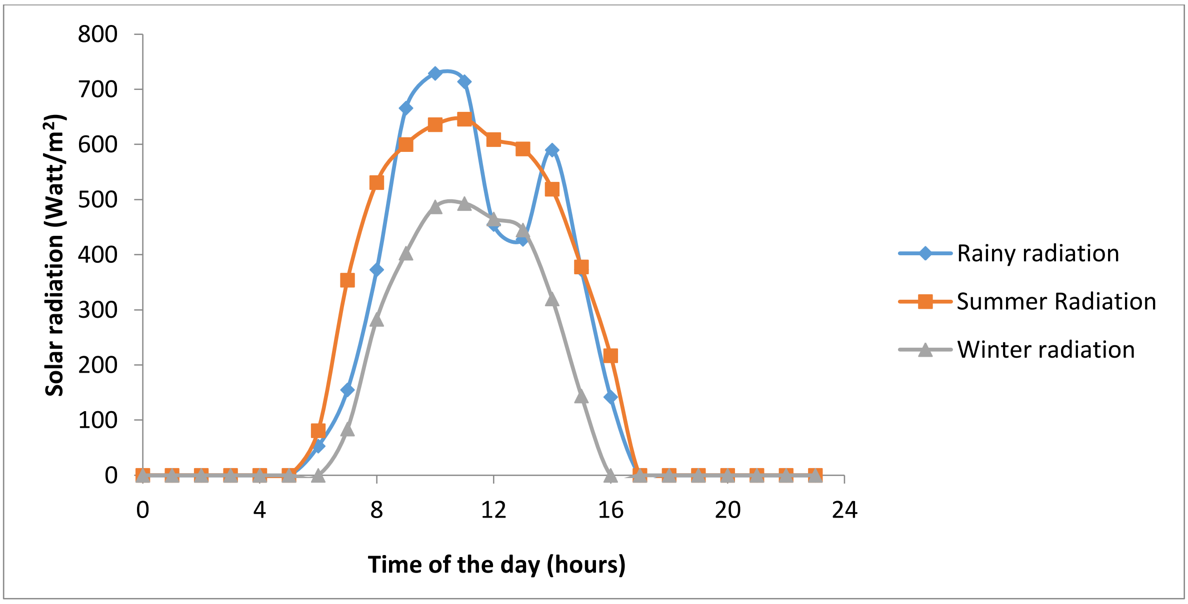


Figure 4.3: Solar radiation pattern for various seasons **(India solar resource data, 2017)**

The variation of wind speed at 50m elevation is given in **Figure4.4.**

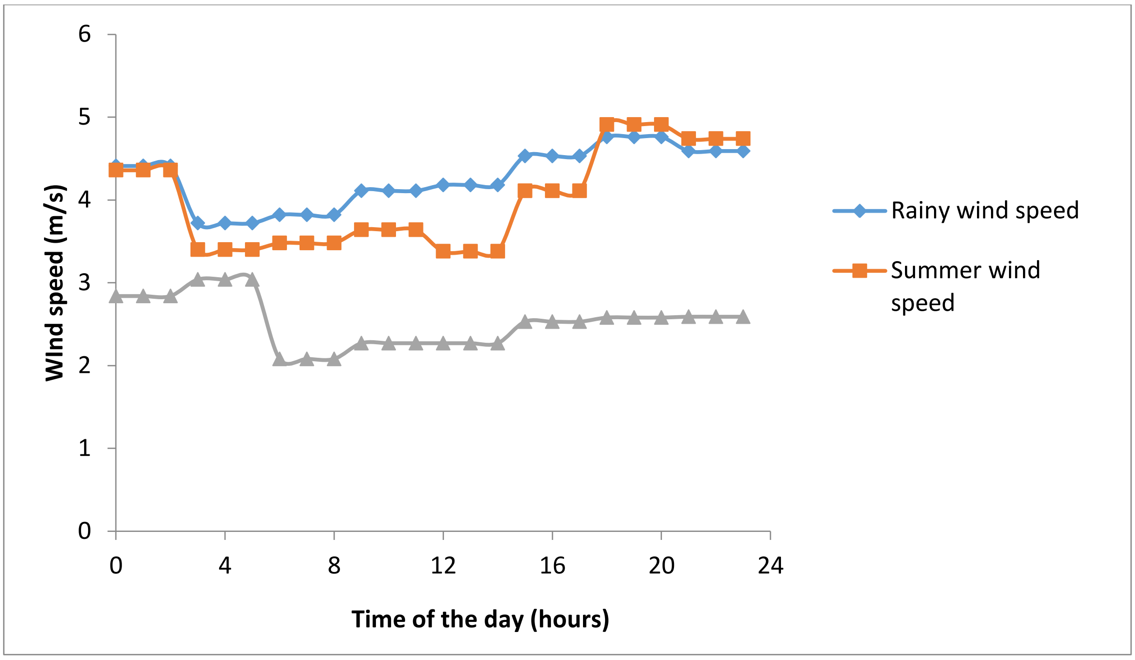


Figure 4.4: Variation of wind speed in different seasons **(NASA surface meteorology, 2017)**

The load curve is dependent on the number of households of a particular village and the appliances used by the villagers. In villages the load is mainly residential and agricultural load as industries are practically nonexistent in these areas. The gadgets used by the villagers and their power consumption are given in Table 4.1(WBSEDCL, 2017).

Table 4.1: Gadgets used in rural areas

Gadgets used	Power consumption (Watt)	Number per household
Tubelight	55	2
Incandescent bulb	60	1
Mobile charger	5	2
Fan	60	2
Street light (Tubelight)	55	20 in total village
Agricultural pumpset	400	5 in total village

The load curve is essential to design the polygeneration system as the availability of resources like solar radiation and wind vary over a day as well as in different seasons. Optimum utilization of these resources is essential for the economic operation of the polygeneration plant. The total load

(TL) at any instance is given by Eqn. 4.1(Ray et al, 2017).

$$TL = DL + AL + SL \tag{4.1}$$

where DL is the domestic load, AL is the agricultural load and SL is the street light load..

4.2.1.1. Modeling of the solar photovoltaic system

The instantaneous power output of the solar module P_{solar} is given by

$$P_{solar} = \frac{PV(m) \times R(t)}{10^6} \tag{4.2}$$

PV (m) is the power output of the solar module at 1000 W/m^2 and R(t) is the radiation incident on the module at the tth instant.

4.2.1.2. Modeling of the wind turbine

The instantaneous power output of the wind turbine, P_{wind},is given by Eqn. 4.3**(Saad, 2018)**

$$P_{wind} = 0.5 \times A \times \sigma \times v\,(t)^3 \times C_p \tag{4.3}$$

Where A is the swept area of the wind turbine, σ is the wind density, v(t) is the velocity of the wind and C_p is the Betz limit (0.59).

4.2.1.3. Modeling of the biomass gasifier

The load fed by the biomass power, $P_{bio}(k)$ at kth instant is given by

$P_{bio}(k) = L(k) - P_{solar}(k) - P_{wind}(k)$(4.4)

Where $L(k), P_{solar}(k)$and $P_{wind}(k)$ are the total load, the load fed by solar power and the load fed by wind power respectively.

4.2.2. Economic modeling

4.2.2.1 Cost of the solar module

The cost of the solar module C_{pv} is given by$C_{pv} = C_{pvperkW} \times PV_{installed}$ (4.5)

where$C_{pvperkW}$ is the cost of solar module per kW and $PV_{installed}$ is the installed capacity of PV module.

4.2.2.2. Cost of the wind turbine

The cost of the wind turbine C_{wind} is given by

$$C_{wind} = C_{windperkW} \times W_{installed} \tag{4.6}$$

where$C_{windperkW}$ is the cost of the wind turbine per kW and $W_{installed}$ is the installed capacity of wind turbine.

4.2.2.3. Cost of biomass gasifier

The cost of the biomass gasifier is given by the Eqn. 4.7 **(Jana and De, 2015)**.

$$C_{eqb} = C_{eqa}\left(\frac{Capacity_b}{Capacity_a}\right)^s \tag{4.7}$$

Where C_{eqb} is the cost of biomass gasifier of capacity b, C_{eqa} is the cost of biomass gasifier of capacity a and s are the scale factors.

4.2.2.4. Cost of ethanol synthesis and separation

The syngas from the gasifier is fed to the ethanol synthesis unit for ethanol production. Pure ethanol is obtained after separating it from the water and unconverted syngas in the ethanol separation unit.

$$TC_{esyn} = 7.4 \times 10^6 \times \left(\frac{E_{thy}}{31176000}\right)^{S_e} \tag{4.8}$$

where, TC_{esyn} is the total cost of the ethanol synthesis unit E_{thy} is the total ethanol synthesized per year and S_e is the scale factor for the costing of the ethanol synthesis equipment.

$$TC_{esep} = 64.4 \times 10^6 \times \left(\frac{E_{thy}}{31176000}\right)^{S_s} \tag{4.9}$$

$TC_{esep}$is the total cost of the ethanol separation unit, E_{thy} is the total ethanol synthesized per year and $S_s$is the scale factor for ethanol separation unit.

4.2.2.5. Reliability analysis

Here the variation of the profit against the reliability of the system is carried out for three different cases, say, (i) designing the system to cater only the least load i.e. when the chance of power failure is highest (ii) designing the system to cater to the average load i.e. the chance of power failure is moderate and (iii) designing the system to cater to the highest load i.e. the chance of power failure tends to zero. The reliability analysis is done by following the loss of power supply probability (LPSP) and unmet load (UL) probability method **(Sinha and Chandel, 2015)**.In the LPSP method, both the time of power failure and the magnitude of the power deficit are considered whereas in UL method only the total time of power failure is considered.

$$LPSP = \frac{\sum_{i=1}^{i=n} E_{deficit}}{\sum_{i=1}^{i=n} P_{load}} \times 100 \qquad (4.10)$$

where $E_{deficit}$ is the total electrical energy deficit over a year and P_{load} is the total electrical energy required per year.

$$UL = \frac{\sum_{i=1}^{i=n} P_{failure}}{\sum_{i=1}^{i=n} P_{total}} \qquad (4.11)$$

$P_{failure}$is the total time when there is electricity deficit and P_{total} is the total hours of operation of the plant.

4.2.2.6. The levelized cost of electricity (LCOE)

The levelized cost of electricity is given by Eqn. 12

$$LCOE = \frac{C_{Mos_2}+C_{Straw}+C_{PV_{module}}+C_{BG}+TC_{ethsyn}+TC_{ethsep}+C_{vam}}{E_L} \qquad (4.12)$$

Where C_{Mos_2} is the cost of catalyst per annum, C_{Straw} is the annual cost of purchasing straw, $C_{PV_{module}}$ is the annualized cost of solar PV module, C_{BG} is the annualised cost of biomass gasifier,$TC_{ethsyn}$is the annualized cost of ethanol synthesis unit, $TC_{ethsep}$is the annualised cost of ethanol separation unit,C_{vam} is the annualized cost of waste heat recovery vapor absorption cooling system and E_L is the total units of electricity generated per year. Straw is produced as a byproduct of paddy cultivation in this area. The straw which remains in excess after feeding the cattle is used in this polygeneration. As straw is collected from the small village spreading over a small area, very little transportation is required. So, the cost of transportation of straw is not considered while calculating LCOE.

4.2.3. Optimization Scheme

In this study optimization is done by relational linear programming (Kersting et al, 2017). The flow chart for optimization scheme is shown in **Figure4.5**.

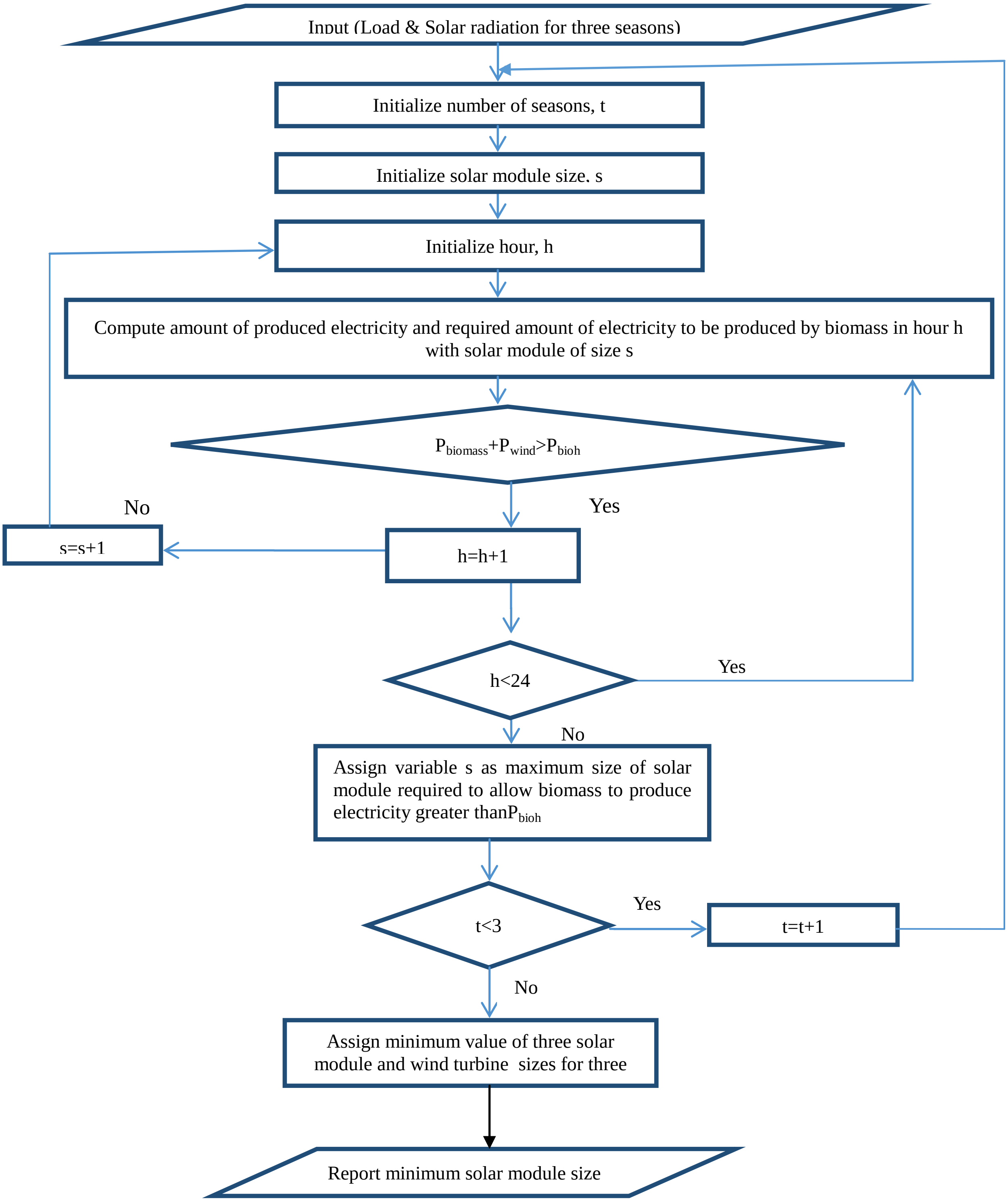


Figure 4.5(a): Flow chart for determination of solar module and wind turbine when there is no shortage of supply of waste heat to WHRVAM

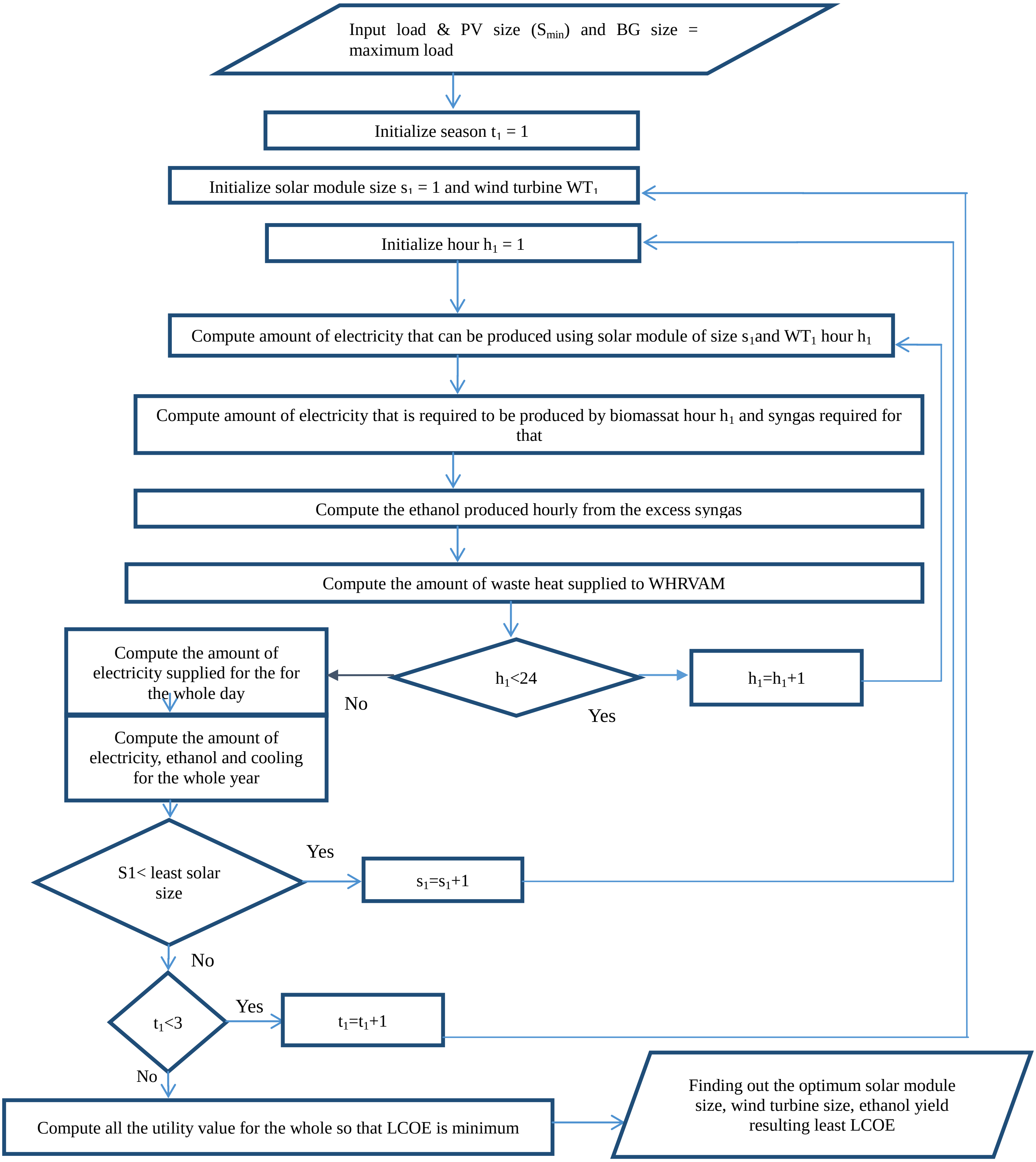


Figure 4.5(b): Flow chart for determination of optimum size of solar module, gasifier, wind turbine and ethanol producing units

Sizes of the solar module, wind turbine are the inputs to the optimization problem. The instantaneous availability of solar radiation (Watt/m^2) and wind speed (m/s) are the constraints to this optimization problem. The size of the biomass gasifier (kW$_e$) corresponds to the maximum load. The more power from solar and the wind turbines lead to more ethanol synthesis. The waste heat needed to run the waste heat recovery vapour absorption system comes from the gas engine. So, a minimum amount of biomass has to be generated at all instances which is another constraint of the optimization problem. The solar module size and the wind turbine sizes are varied. This study is carried out for a village of India inhabited by poor people. So, to make the system sustainable in this area LCOE is chosen as the objective function from the socio-economic point of view. The LCOE as shown in Eqn. 4.12 is the objective function. The minimization of LCOE is the objective function. The size of the solar module, wind turbine, the biomass gasifier and the ethanol producing units that lead to the least LCOE is the optimized size of the components.

4.3. Results and discussion

Table 4.2 contains inputs for economic calculation.

Table 4.2: Input data for economic calculation

Serial No	Parameter	Value
1	Cost of straw	0.13 USD/kg
2	Cost of PV module	0.88 USD/Watt-peak
3	Cost of ethanol	0.66 USD/liter **(Jana and De, 2015)**
4	Operating hours per annum	8000 hours
5	Plant life	20 years
6	Scale factor for biomass gasification	0.6 **(Jana and De)**
7	Scale factor for ethanol synthesis	0.7**(Jana and De, 2015)**

The optimized size of the components is given in Table 3. The optimized LCOE is 0.1081USD/kh.

Table 4.3: Optimized size of components

Serial No	Parameter	Value
1	Electrical output of biomass-gas engine	219 kWe
2	Capacity of Solar PV module	6 kW
3	Capacity of wind turbine	3.23 kW
4	Size of the vapor absorption chiller	3 ton of refrigeration
5	Yearly ethanol production	2919.3 liters

The hybridization of more types of renewable energy resources leads to decrement of LCOE It is shown in **Figure4.6**.

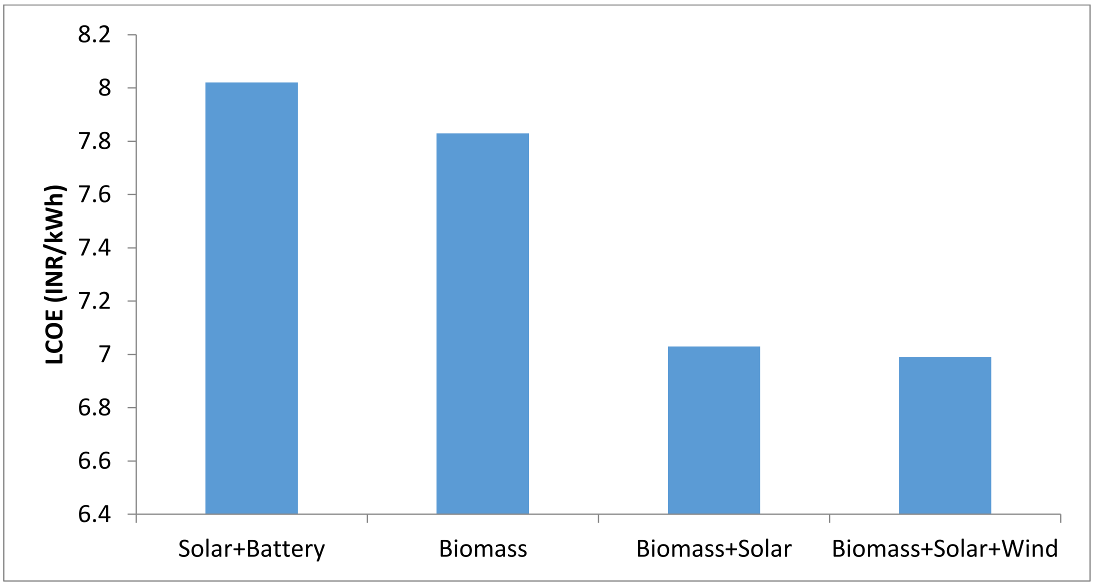


Figure 4.6: Variation of LCOE with hybridization

It occurs because renewable energy resources are intermittent in nature. At the instant when one resource is absent, other may be available in abundance at the same site, say, in the rainy season solar resource availability is intermittent but the availability of wind resource is high. Thus more hybridization of power system in a single system leads to better resource utilization.

In this study it has also been shown that addition of utilities in a single efficiently integrated system lowers the LCOE as shown in **Figure4.7**.

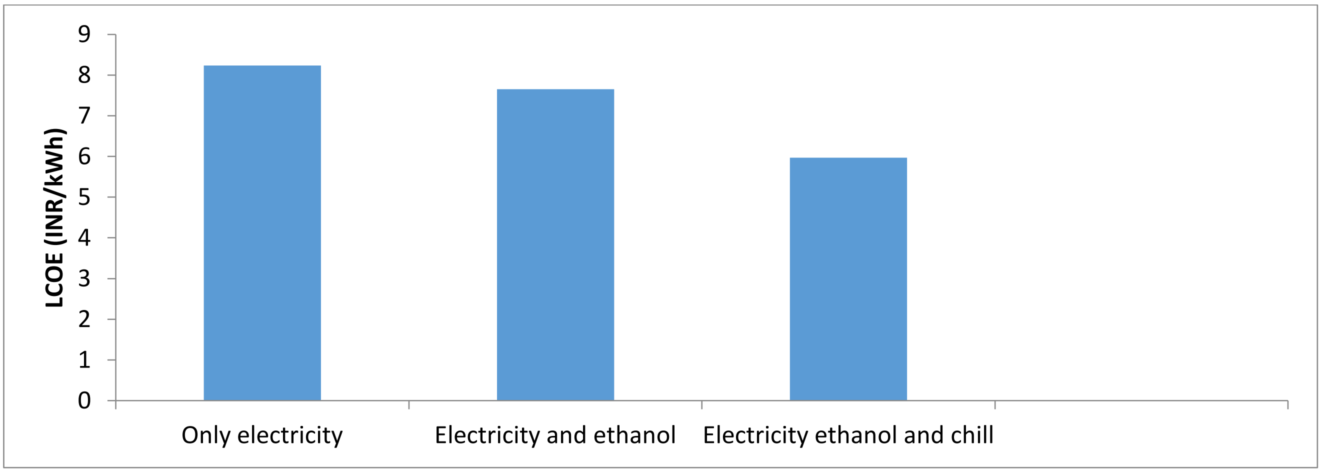


Figure 4.7: Variation of LCOE with addition of utilities

The LCOE is found to be 8 INR with only electricity as the utility output and it has reduced to 6 INR with addition of other utilities. This is also a socially acceptable solution as ethanol is also important to the villagers as the local transportation fuel and chilling is required for food or crop storage.

4.3.1 Sensitivity analysis

The prices of the components change with time due to technical as well as the economic factors. So sensitivity analysis is required to study the suitability of the system in the varying environment. **Figure4.8** shows variation of LCOE with the straw cost.

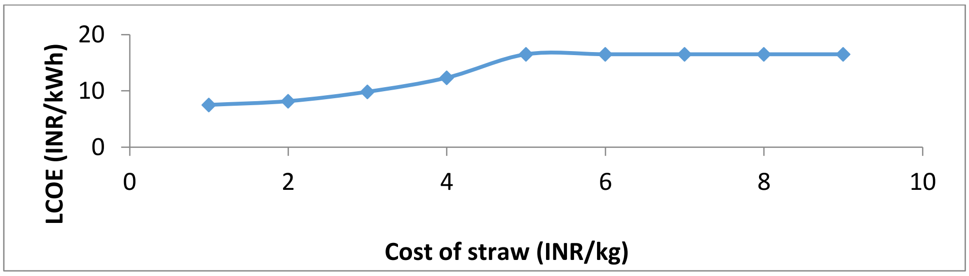


***Figure4.8:** Variation of LCOE with cost of straw*

Straw is the feedstock to the biomass gasifier which is the principal electricity generator. Moreover, the syngas generated by the biomass gasifier is used to produce ethanol. If the cost of straw decreases below 4.5INR/kg then the LCOE rapidly decreases. This is due to the combined effect of decrease in the cost of the feedstock for electricity generation and increase in the optimized amount of synthesized ethanol.

Figure 4.9 shows the variation of LCOE with the unit price of solar module. It is observed that there is a parallel shift in the graph if the solar module price decreases below 39.60 INR/W_p. This is because if the solar module price becomes less than 39.60INR/W_p then the optimized solar module size becomes 8kW for minimum LCOE and the capacity of the wind turbine becomes 1kW as wind resources availability is lesser than solar resource availability.

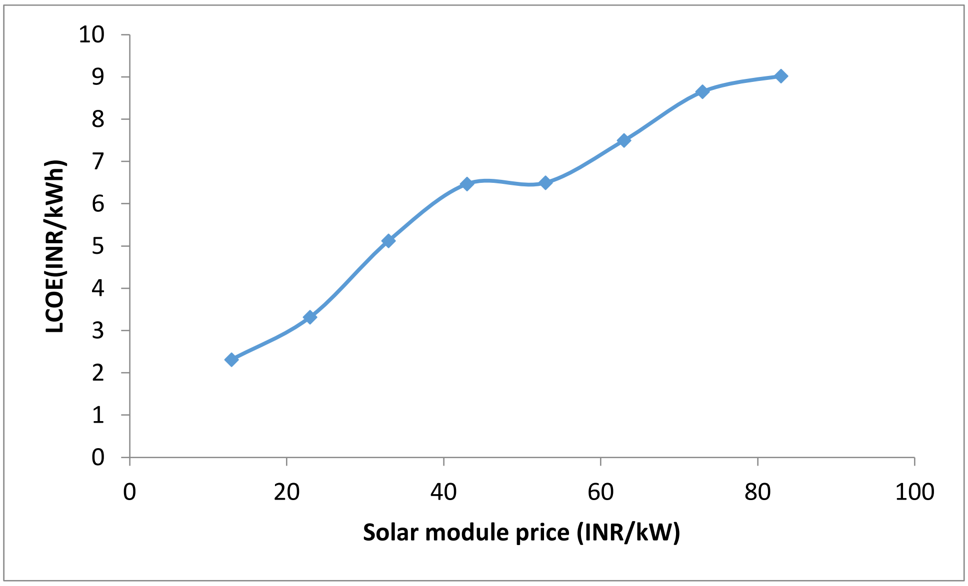


Figure4.9: Variation of LCOE with cost of module

Figure 4.10 shows that LCOE decreases with the increase in the reliability of power supply. This is because renewable energy systems have much higher initial cost than the running cost.

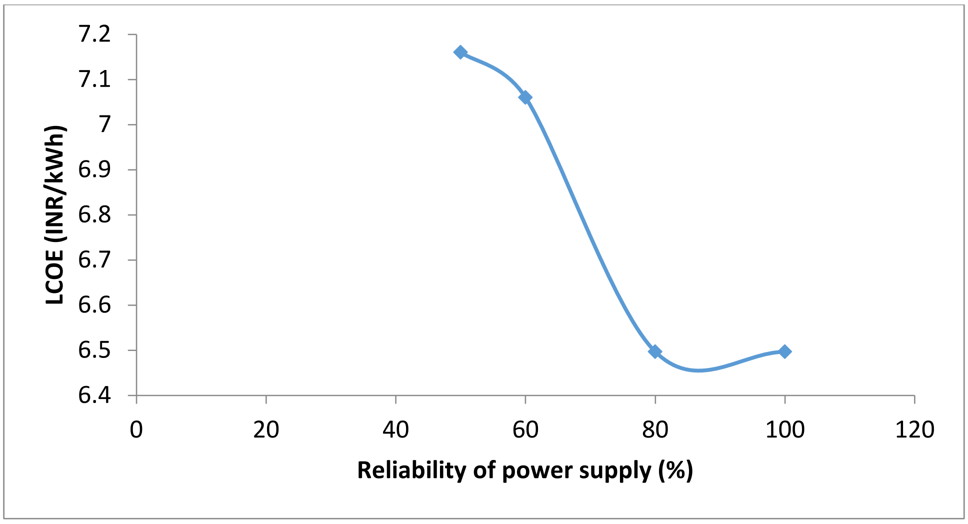


Figure 4.10: Variation of LCOE with reliability of power supply

In the hours of power failure, there is no revenue but the initial investment is already done. Moreover the cost of the major electricity generator i.e. the biomass gasifier does not decrease linearly with the decrease in size. So there is a decrease in LCOE with the increase in reliability of power supply which is a socially acceptable solution. **Figure 4.11** shows variation of LCOE with the life of the plant.

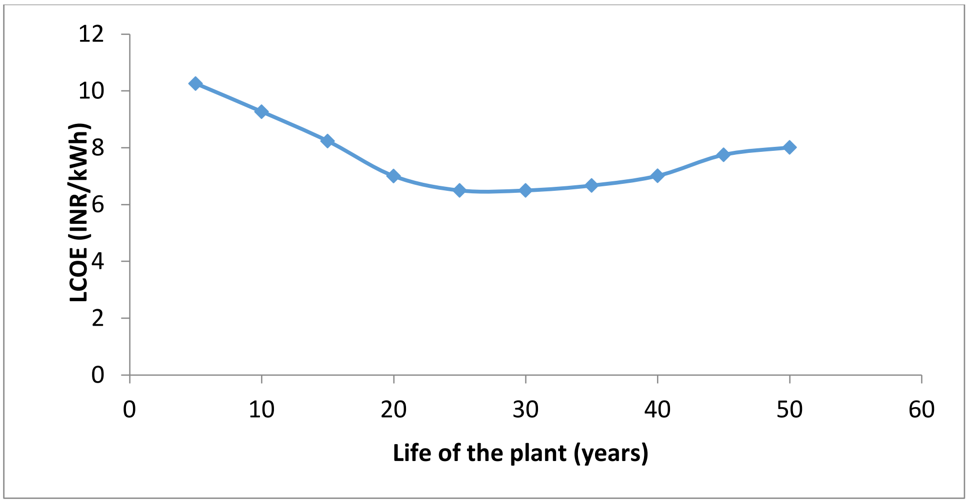


Figure 4.11: Variation of LCOE with life of the plant

It is observed that for the economic operation of the plant, the minimum plant life is 20 years or above. This is because the capital recovery factor (CRF) depends on the plant life. The higher the plant life lower is the CRF. The annualized cost is obtained by multiplying the CRF with the total investment. If the CRF is higher, then the annualized investment increases leading to higher LCOE.

4.4. Conclusions

Development of polygeneration system with the renewable sources of energy may be a sustainable option. These systems have multiple inputs and multiple outputs. Application of proper optimization algorithms is necessary for the design and economic operation of these systems. The minimum life of the plant is twenty years for the economic operation of the plant. Results of the study show that the levelized cost of electricity decreases with the hybridization of more renewable resources in the same system. The levelized cost of electricity decreases with the increase in the reliability of the system by 50% which is a better socially acceptable solution. The levelized cost of electricity is 6.50 INR/kWh. The levelized cost of electricity abruptly increases if the cost of straw increases to even more than 5 INR/kg.

5. Distributed polygeneration using local resources for an Indian village: multi objective optimization using metaheuristic algorithm

5.1. Introduction

The consumption of energy and economic development are very closely linked. Developed societies generally has per capita energy consumption higher than that of the developing societies (Tomam and Barbora 2003). Presently the world is mostly dependent on the fossil fuel resources for the supply of energy. Currently around 78% of electricity need of the world is met by the centralized fossil fuel based power plants. Out of the fossil fuels, coal is most predominant (around 40%) followed by the natural gas and petroleum respectively (US Energy Information Administration 2017).There is an expectation of 40% rise in energy consumption by 2040 (USDOE 2016).But fossil fuel reserves are also fast depleting besides having several environmental impacts; most severe is the global warming due to green house gas (GHG) emission. Coal based power plants emit 50g-CO$_2$equivalent/kWh even with best practices (UK Carbon Footprint 2016).The Intergovernmental Panel on Climate Change (IPCC) has predicted -16 ° to -14° Fahrenheit rise in global average temperature by 2100 (Climate Change 2016). There is a need to use of renewable sources of energy which are non depleting and clean in terms of GHG emission. However, these renewable resources are intermittent and dilute in nature. Moreover limited amount of these resources are available at a particular location depending on the geographical conditions and several other factors including population, livelihood of the local people etc. So to increase the capacity further technology development with scaled up systems are necessary. Another option is to combine different renewable resources available in a particular locality to increase the capacity of the electricity generation with these limited intermittent resources. This is formally called “hybridization”. The technological development of the renewable energy systems are still developing and scaling up of renewable energy systems for large power supply is yet to be matured. Small scale distributed systems may be a better option at present. These systems reduce the transmission and distribution (T&D) loss and capacity can be optimized with the available resources and local demand. These systems are also good options to electrify the un-electrified hamlets in India where the extension of national grid is impossible due to terrain conditions or other socio economic factors. Integrating other utility outputs in a single unit formally called “polygeneration” makes it even more beneficial and socio economically feasible. So these systems need to be designed matching with the local electricity load and other utility requirements. The process integration and generation of useful chemicals enhance the environmental and economic sustainability of systems (Sadhukhan et al 2015). The design of the polygeneration systems has several objectives as well as constraints and boundary conditions. It has been observed that even in the conventional coal fired power plants synthesis of other chemicals through the polygeneration route proves to be beneficial both thermodynamically and economically (Ng et al 2012). So multi criteria optimization is the only option for designing these systems based on the objectives of policy and planning.

Several optimization algorithms exist but all may not be suitable for optimizing a particular system. Hence the choice of suitable algorithm is also another important issue in this regard. Chauhan et al.(Chauhan and Saini 2016)used the discrete harmony search based optimization technique for designing the Integrated Renewable Energy System for supplying electricity to some un-electrified villages of the Uttarakhand state of India. Jana and De (Jana and De 2015 a)designed a suitable polygeneration system using biomass as the local resource. They have shown that 20% of the primary energy savings is achieved by the process integration. This also leads to the reduction of 25kt carbon –dioxide emission per annum. George Kyriakarakos et al.(Kyriakarakos et al 2011) presented a concept of designing a polygeneration system using a battery bank, proton exchange membrane (PEM) fuel cell, PEM electrolyzer and a metal hydride tank, a reverse osmosis based desalination unit using heat recovery and control system for the supply of power, potable water and hydrogen as the transportation fuel. They have used the Monte Carlo simulation method to take the uncertainty into account. Results of their study show that the polygeneration is technically feasible and profitable with a probability of 90% at present and 100% in the medium term. The use of renewable energy sources like biogas has proved to be efficient economically in UK perspective (Sadhukhan 2014) Ng et al proposed a polygeneration scheme producing bio oil. The bio oil can be treated as an environmentally benign feed stock but at the same time the economic competitiveness of the bio oil was yet to be judged. The polygeneration scheme along with the electricity generation is shown in (Ng et al 2011).Ng et al shows that the addition of chemicals in addition to the electricity increases the economic competitiveness of the polygeneration system (Ng et al 2013). Ng et al have done a comparative study between the biomass gasification combined cycle (BGCC) and biomass gasification fuel cell system (BGFC). It was found that BGFC system provides twice power than that of the BGFC system. It is observed that increasing power generation from BGFC system decreases the power generation efficiency but at the same time the combined heat and power (CHP) efficiency increases (Sadhukhan et al. 2010).Hoon Loong Lam (Lam et al. 2016)proposed that process integration is an efficient way for energy savings and energy targeting. This chapter has emphasized on the recovery of the industrial process heat. Saeed Belgana (Belgana et al 2013) designed a hybrid renewable energy system with photovoltaic (PV) panel, wind turbine, diesel generator set and a battery bank using the Multi Objective Optimization technique to optimize the annualized system cost and the reliability of power supply of the system. Economic feasibility and environmental effect assessment have to be assessed before the introduction of a new renewable energy system. So, optimization of a new small scale renewable energy system is a multi-criteria problem. Kriakarakos et al.(Kriakarakos et al 2015)designed a polygeneration system using multi crystalline solar module, fuel cell, electrolyser unit, desalination unit. In this system the battery can be replaced by a capacitor bank with more intensive use of hydrogen based systems. Ng et al. showed that there is a significant improvement in the thermodynamic and economic potential through suitable balanced polygeneration system (Ng et al. 2012).

These groups of authors are studying polygeneration as a sustainable energy solution from different viewpoints over a period. Starting from component design (Jana and De 2015 a, Jana and De 2015 b), performance assessment (Jana and De 2015 c), economic feasibility study with real data(Jana and De 2015 d), environmental impact assessment(Jana and De 2017, Jana and De 2016)and finally possible optimization with definite objective functions and real boundary conditions (Ray et al. 2017)are reported in their several publications. In this chapter a multi criteria optimization study is carried out using a metaheuristic algorithm "Cuckoo Search Algorithm (CSA)" to determine a possible optimum solution for a distributed generation with three utility outputs and using local renewable resources only. Real data of a typical Indian village of northern hilly area of the state of Uttarakhand has been studied in this work. Extension of national grid to this area is practically not feasible due to terrain conditions. An estimation of the feasibility and possible optimum solution with multi objectives and several boundary conditions and constraints are done using CSA. A comparison with the other algorithms like genetic algorithm (GA)and particle swarm optimization (PSO) has also been made. The codes of all these algorithms are developed in MATLAB 2013. Methodology is generic for such optimization problems but, the results may vary depending on the type of system, available data, constraints and boundary conditions. In this case the site specific study is done. The muli-objective optimization using a metaheuristic algorithm i.e. Cuckoo Search Algorithm is carried out here. Obtained results may be useful for the policy makers to decide feasibility of future introduction of such distributed polygeneration system using local resources as a possible future sustainable solution.

5.2. Materials and methods

In this chapter, a distributed polygeneration system has been proposed to meet the local energy needs of a small village in India. This area has solar, wind, cattle dung (biogas resource) and biomass (straw) resources, which can be used to cater to the energy demand of the local people. The optimum capacities of the various components of the polygeneration system for minimized levelized cost of electricity (LCOE), land requirement and greenhouse gas (GHG) emission are estimated by CSA. The three utility outputs are electricity, cooking gas with high calorific value and heat. Till date no standardized power dispatch strategy is there for the multigeneration system. However, ‘ideal predictive power dispatch strategy’ is used in this hybrid system. This strategy is used as this proves to be economically the best solution for decentralized power plants using hybrid renewable energy systems (Barley and Winn, 1996).The electricity is fed to the local micro grid of this polygeneration to meet the local demand matching the load curve. This village is located in a very cold area with occasional snowfall during winter, moderate rainfall during monsoon and a mild summer(National Institute of Disaster Management, 2016). In such villages, there is a need for heating which is included as a utility output in this polygeneration system. Excess hydrogen, which is not used to produce electricity, will be mixed with the biogas and thereby enhancing the calorific value of the biogas. The capacities of the components of the proposed polygeneration system are optimized using CSA with three objectives i) To minimize the LCOE ii) To minimize land requirement iii) To minimize GHG emission. The multi objective optimization is carried out using weighted sum method. Comparison has also been made with a few other meta heuristic algorithms like genetic algorithm (GA) and particle swarm optimization algorithm (PSO), with number of iterations constant for all the cases.

5.2.1. System Description

The proposed renewable energy based polygeneration system is modeled using solar PV module, wind turbine, gasifier-gas engine, biogas digester, PEM electrolyzer and a PEM fuel cell as shown in **Figure5.1.**During the daytime, the solar module generates power which is fed to the local microgrid to meet the local load. The domestic and the agricultural load are predominant in this region as industries are practically nonexistent in such rural areas of India.

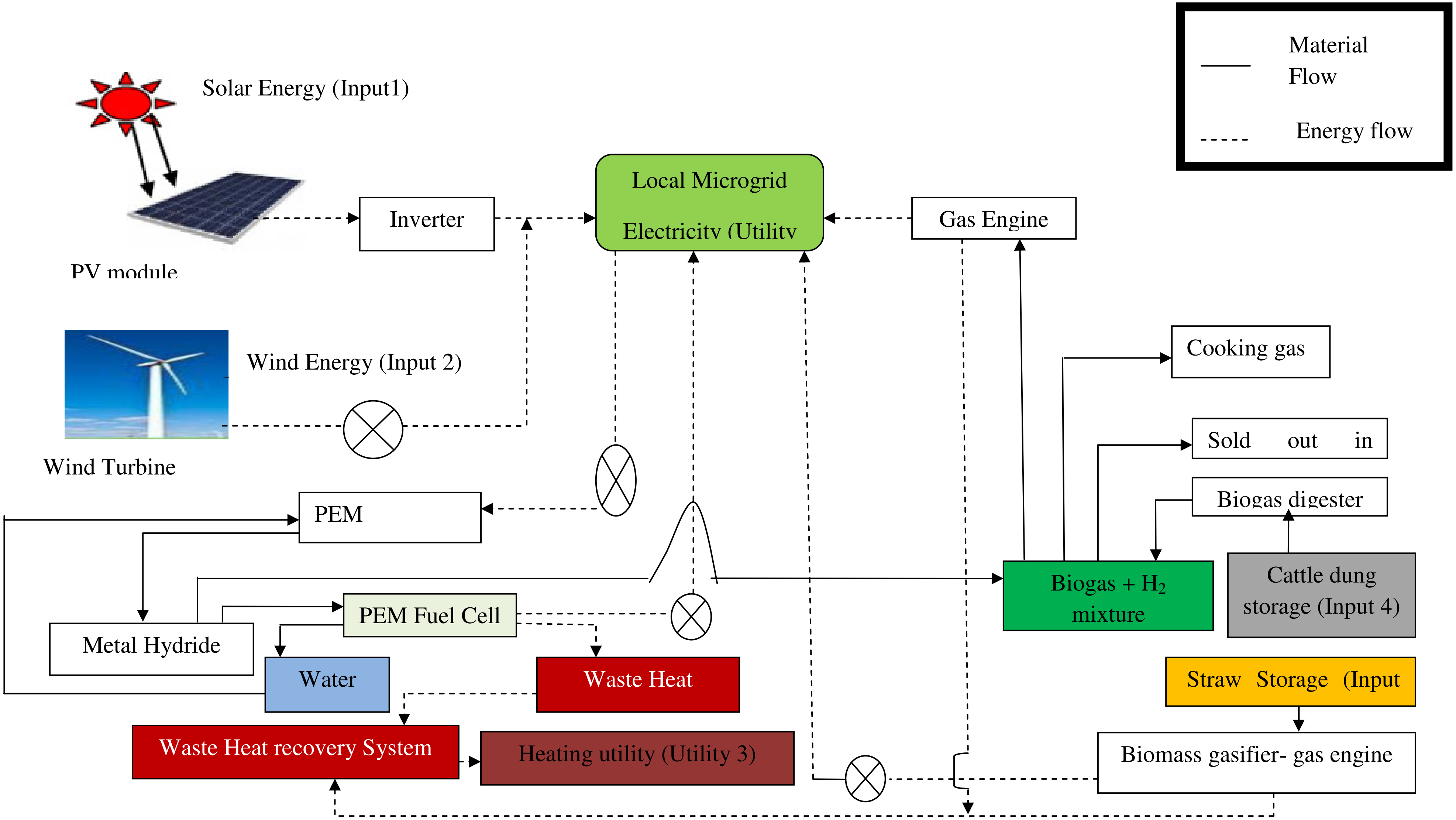
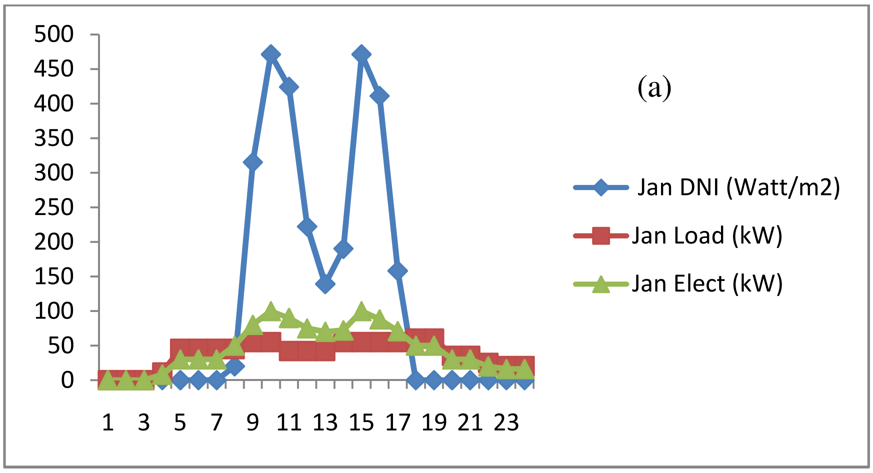
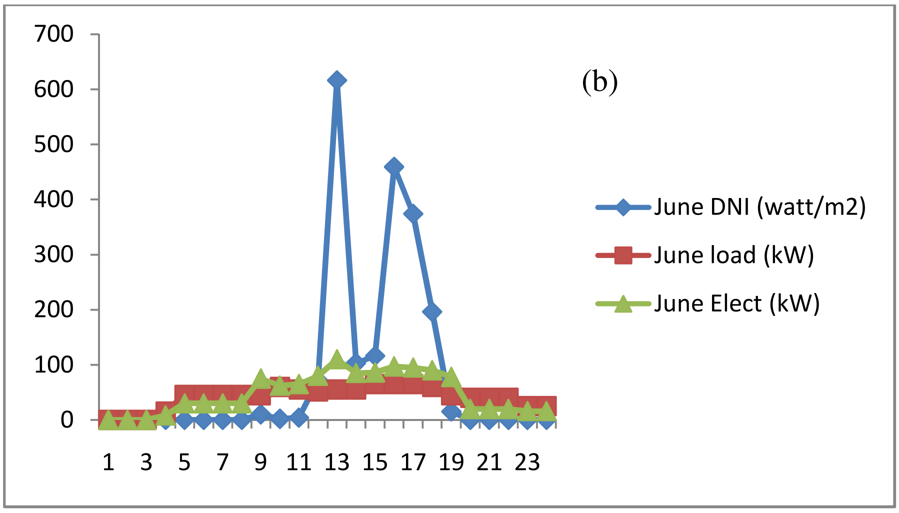
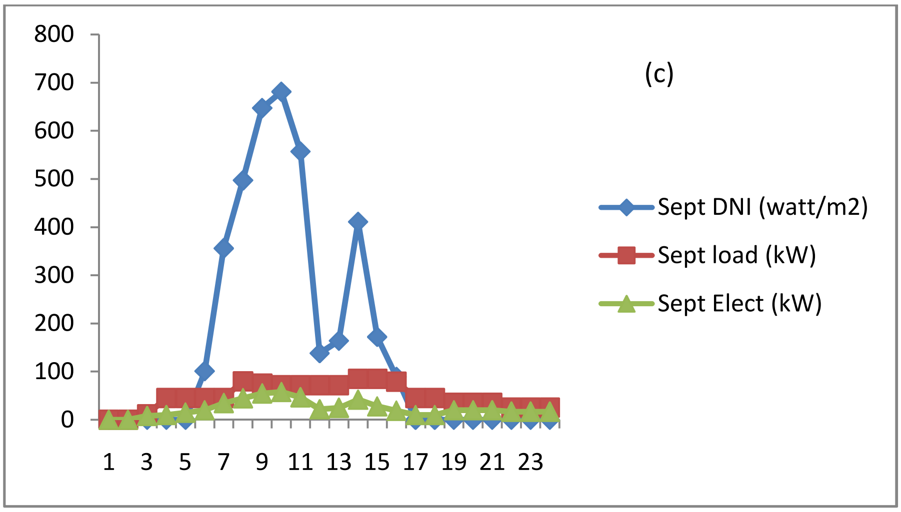


Figure5.1: Schematic of the polygeneration system

The seasonal variations of loads along with the electricity generation from the solar and wind resources in the four different seasons are shown in **Figure 5.2(a)-(d).**







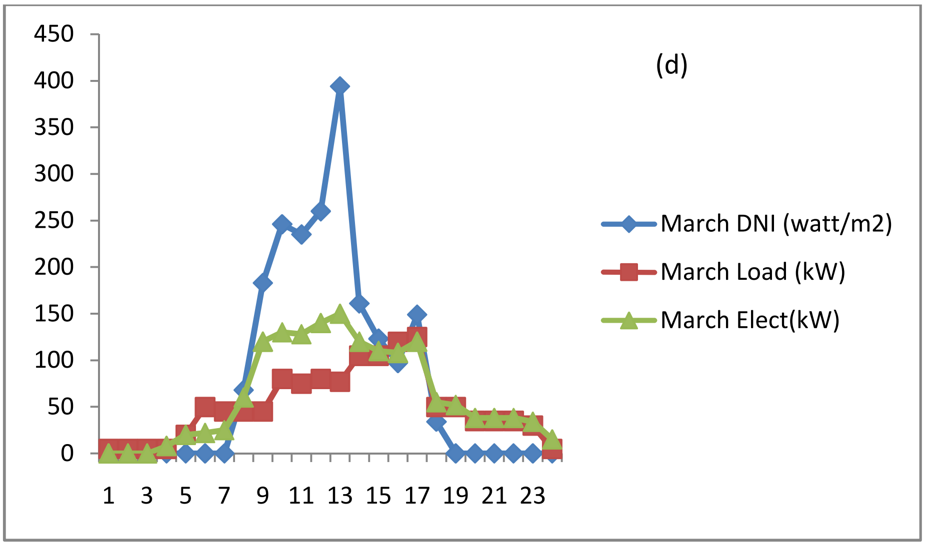


Figure5.2: Load curve and solar radiation pattern of (a) winter (b) rainy (c) autumn (d) summer

The excess electricity after meeting the load is fed to the PEM electrolyzer to produce hydrogen, which is stored in the metal hydride tanks. The metal hydride storage is used as it is safer and volume efficient than other hydrogen storage options(Muller and Marmejo 2017). The hydrogen stored is used in a PEM fuel cell to produce electricity and waste heat. The capacity of the electrolyzer is estimated so that it can cater to the maximum load even in absence of solar energy. So when the load is low, there is excess hydrogen. The excess hydrogen is stored in metal hydride tanks. The stored hydrogen is mixed with the biogas for higher calorific value (CV) of the gas mixture. The resultant gaseous mixture contains hydrogen and biogas in the ratio of 2:3.During night hours, the electrical load is met by the electricity coming from the fuel cell, the gas engine and the wind turbine. The quality of fuel cell water is distilled water standard(Tibaquira et al. 2016). It is again fed back to the electrolyzer.

5.2.1.1. Modeling of the PV system

The solar insolation is incident on the solar panels generating electricity. The module is placed south facing. The total solar radiation on a tilted surface is given by **Eqn. 5.1**(Ghribi et al. 2013). The solar system modeling is done in TRNSYS17 as shown in **Figure5.3.**

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \tag{5.1}$$

Where I_T is the total radiation on a tilted surface, I_b is the beam radiation on a tilted surface, r_b is the tilt factor for beam radiation, I_d is the diffuse radiation, r_d is the tilt factor for diffuse radiation, r_r is the tilt factor for the reflected radiation. For this case the reflected radiation is assumed to be negligible.

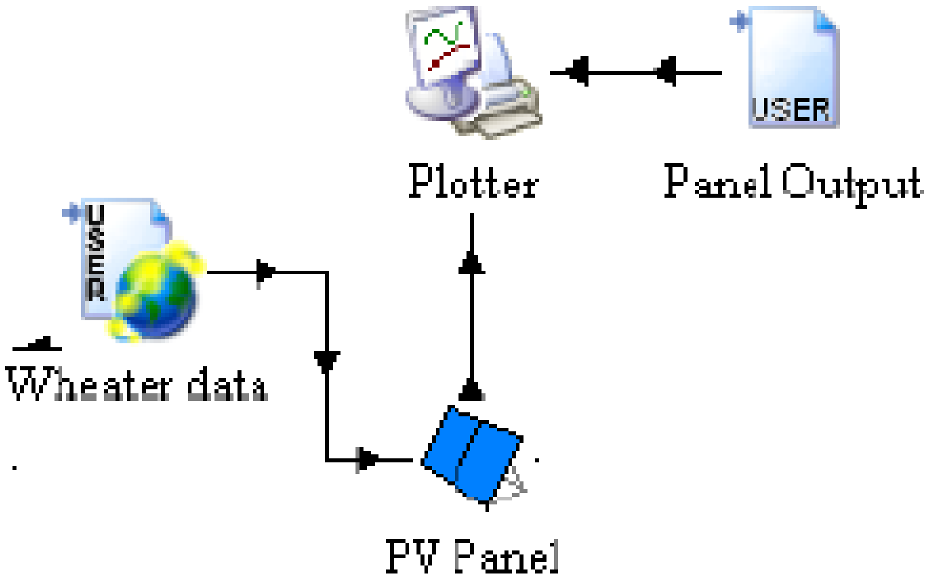


Figure 5.3: TRNSYS model for output of a Solar PV module

The tilt factor for the beam radiation r_b for a south facing surface is given by **Eqn. 5.2** (Solanki 2009).

$$r_b = \frac{Cos\theta}{Cos\theta_Z} \tag{5.2}$$

Where θ is the incidence angle of the solar insolation and θ_Z is the zenith angle.

The angle of incidence θ for a south facing surface is given by **Eqn. 5.3** (Solanki 2009)

$$Cos\theta = Sin\delta Sin(\varphi - \beta) + cos\delta cos\,\omega cos(\varphi - \beta) \tag{5.3}$$

Where δ is the declination angle, β is the slope of the collector, which is equal to the latitude of the place for this chapter, φ is the latitude and ω is the hour angle.

The Zenith angle θz for a collector facing south is given by **Eqn. 5.4**(Sukhatme 2003)

$$Cos\theta_Z = sin\delta \sin(\varphi - \beta) + \ cos\delta \cos(\varphi - \beta) \cos\ \omega \qquad (5.4)$$

The tilt factor for diffuse radiation $r_d$is given by**Eqn. 5.5**(Sukhatme 2003)]

$$r_d = \frac{1 + Cos\beta}{2} \qquad (5.5)$$

The tilt factor for the reflected radiation is given by

$$r_r = \frac{(1 - Cos\beta)\rho}{2} \qquad \text{Where}\rho \text{ is the albedo} \qquad (5.6)$$

The instantaneous output voltage $V(t)$ and instantaneous output current I(t) of a PV module is given by the respectively(Chauhan and Saini 2016)

$$V(t) = V_{max}[1 + 0.0539 \log\left(\frac{I_{incident}}{I_{standard}}\right)] + \alpha T_a(t) + 0.02 I_{incident} \qquad (5.7)$$

Where $V_{max}$the open circuit voltage of the module is, $I_{incident}$ is the solar insolation falling on the module at time t and $I_{standard}$ is the standard insolation (1000 W/m^2), $\alpha$is the temperature coefficient of open circuit voltage and T_a is the ambient temperature.

$$I(t) = [I_{sc} + \alpha_1 T_a(t) - T_{(r)}] \times \frac{(I_{incident})}{(I_{standard})} \qquad (5.8)$$

Where$I_{sc}$is the sort circuit current of the module,α_1 is the temperature coefficient of short circuit current and T_r is the reference temperature.

The instantaneous power of the solar module $P_{sol}(t)$is given by

$$P_{sol}(t) = \ I(t) \times V(t) \qquad (5.9)$$

5.2.1.2. Modeling of the biogas system

The biogas is produced in an anaerobic biogas digester from the cattle dung available in the village. The biogas is mixed with the hydrogen in a ratio of 2:3. The mixing of hydrogen with biogas results to produce a gaseous mixture which has higher CV than biogas. Less than 50% of the gaseous mixture is used by local villagers for cooking purpose and meeting electricity load at night. The excess gas is sold out. The rest is used in the gas engine to produce electricity at night as estimated by **Eqn. 5.10.**

$$P_{biogas}(t) = \frac{BG_{avail} \times CV_{bio} \times \eta_{bio}}{OP} \tag{5.10}$$

Where BG_{avail} is the biogas available per day, $CV_{bio}$is the calorific value of the biogas,η_{bio} is the efficiency of the gas engine and OP is the operating period (in hours) of the engine per day.

5.2.1.3. Modeling of the PEM electrolyzer

The instantaneous amount of hydrogen$H_{elect}(t)$ produced by the PEM electrolyser is given by **Eqn.5.11.**

$$H_{elect}(t) = \frac{E_{elec}(t) \times \eta_e}{CV_h} \tag{5.11}$$

Where $E_{elec}(t)$ is the instantaneous electricity consumed by the electrolyzer, CV_h is the calorific value of hydrogen and η_e is the efficiency of the electrolyzer.

5.2.1.4. Modeling of the PEM fuel cell

The hydrogen generated by the electrolyzer is stored in a metal hydride tank**.** Then the hydrogen is fed to the fuel cell to generate electricity. The electricity generated by the fuel cell E_{fc} is given by **Eqn.5.12.**

$$E_{fc} = H_{fc} \times CV_h \times \eta_{fc} \tag{5.12}$$

WhereH_{fc} is the amount of hydrogen fed to fuel cell,CV_h is the calorific value of hydrogen and $\eta_{fc}$is the efficiency of the fuel cell.

The waste heat generated by the fuel cell W_{fc} is given by**Eqn. 13.**

$$W_{fc} = H_{fc} \times CV_h \times \frac{(100-\eta_{fc})}{100} \tag{5.13}$$

Where H_{fc} is the amount of hydrogen fed to the fuel cell and, $\eta_{fc}$is the efficiency of the fuel cell.

5.2.1.5. Modeling of Wind turbine

The instantaneous power output P_{wind} of a wind turbine is given by**Eqn. 14.**

$$P_{wind} = 0.5 \times A \times \sigma \times v^3 \times C_p \tag{5.14}$$

Where A is the area of the wind front intercepted by the rotor blades, σ is the density of air, v is the wind velocity and C_p is Betz limit.The velocity of wind for this location is taken from NASA website as shown in **Figure5.4** (NASA Surface Meterology 2017)**.**The density of air is assumed as 1 kg/m^3 and the swept area is assumed to be 12.6m^2.

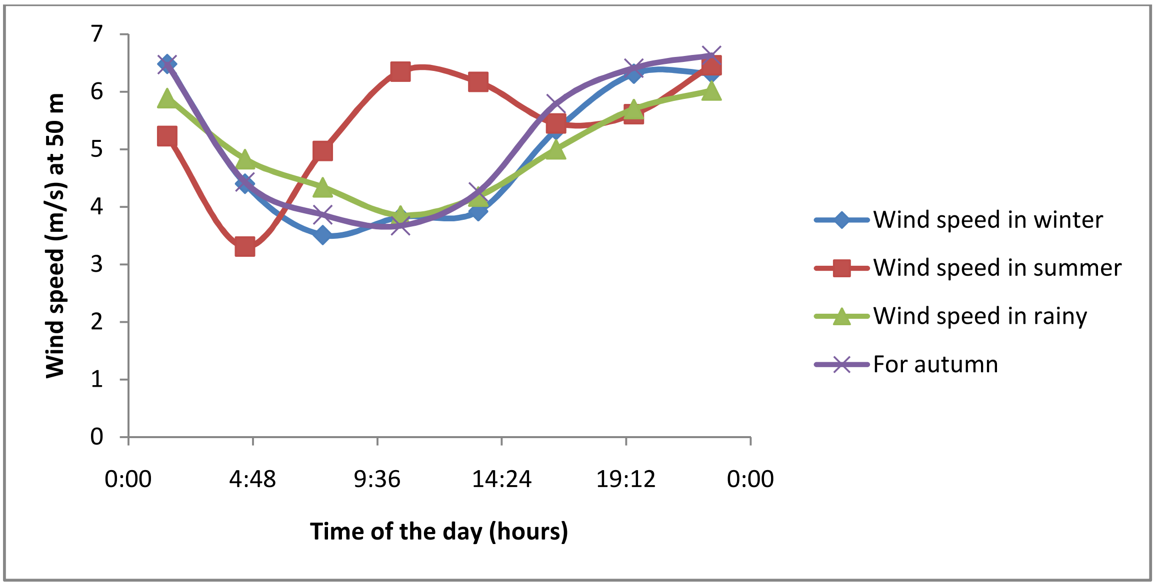


Figure 5.4: Variation of wind speed over a day in various seasons

5.2.1.6. Formation of the gaseous mixture

The gaseous mixture is formed by the mixture of hydrogen and biogas in the ratio of 2:3. The calorific value of 1 kg of gaseous mixture, CV_g is given by **Eqn.5.15**

$$CV_g = 0.4 \times CV_h + 0.6 \times CV_{bio} \quad (5.15)$$

where CV_h is the calorific value of hydrogen and CV_{bio} is the calorific value of biogas.

5.2.2. Load Curve

The load curve or the electricity demand of this study is taken from literature as shown in **Figures 5.2(a)-(d)** (Kanse-Patil et al 2011)**.**

5.2.3. Calculation of Land requirement

The land requirement L for the entire polygeneration is given by

$$L = L_{sol} \times PV_{installed} + L_{bio} \times BG_{installed} + L_{wind} \times W_{installed} \qquad (5.16)$$

Where L_{sol} is the land requirement per kW of PV installation as is shown in **Table 5.1**, PV$_{\text{installed}}$ is the total PV capacity installed, L_{bio} is the land requirement per kW of biogas as shown in **Table 5.1**, $BG_{installed}$ is the installed capacity of the biogas plant. The land requirement of the fuel cell is neglected as it is very small compared to the other three. It is also assumed that the two-biomass based systems (biomass gasifier and biogas digester) will have a large area shared.

Table 5.1: Land requirement for solar , biogas and wind systems (Chauhan and Saini 2016)

Serial No	Name of Renewable Energy Technology	Land Required (m^2 /kW)
1	Solar PV	30
2	Biogas System	144
3	Wind	110
4	Biomass systems	90.20

5.2.4. Calculation of GHG emission

$$G = \mathrm{G_s} \times PV_{installed} + F_g \times F_{installed} + G_d \times BG_{installed} + G_g \times G_{installed} + W_g \times W_{installed} \quad (5.17)$$

where G is the total GHG emission, G_S is the emission factor of solar module, F_g is the emission factor of fuel cell, $F_{installed}$ is the installed capacity of the fuel cell, G_d is the emission factor of the biogas digester , $BG_{installed}$ is the installed capacity of the biogas digester, and G_g is the emision factor of biomass gasifier, $G_{installed}$ is the installed capacity of the biomass gasifier, W_g is the emission factor for wind turbine and $W_{installed}$ is the installed capacity of wind turbine. The emission factors are given in **Table 5.2.** The emission factors considered here are based on the life cycle assessment of the wind, biomass and the solar systems with on the cradle to grave analysis i.e. considering the emissions from collecting the raw materials of the product to their final disposal.

Table 5.2: Emission potential for solar, wind, biogas, biomass and fuel cell systems (Tester et al 2006)

Serial No	Name of component	Emission potential (g-CO_2/kWh)
1	SPV	98
2	Biogas system	70
3	Wind	100
4	Fuel Cell	20
5	Biomass gasifier systems	65

5.2.5. Optimization scheme

5.2.5.1. Cuckoo search

In the present chapter, the comparison of cuckoo search algorithm is carried out with the other metaheuristic algorithm by developing codes in MATLAB 2013. The flow charts for all the algorithms are shown in **Figures 5.5.**Cuckoo Search is a nature inspired metaheuristic algorithm that has been broadly used for solving complex optimization problems(Tester et al 2006)**..** CSA is based on the brood parasitism of the cuckoo species. It also uses a balanced composition of a local random walk and global explorative random walks, controlled by a switching parameter p_a. The local random walk can be defined by the **Eqn. 5.18**(Yang 2014)

$$x_i^{t+1} = x_i^t + \alpha s \ \emptyset H(u)(p_a - \epsilon)\emptyset(x_j^t - x_k^t) \qquad (5.18)$$

$x_j^t$and x_k^t are two different candidate solutions selected randomly by random permutation, $H(u)$is a Heaviside function, ϵ is a random number drawn from a uniform distribution,α is the step size scaling factor and s is the step size. Here, $\emptyset$ stands for the entry-wise product of two vectors.On the other hand, the global random walk is carried out by the Levy flights.

5.2.5.2. Levy Flights

Lévy Flights are capable of maximizing the probability of resource searches in uncertain surroundings. In optical science, Lévy flight can be defined as a term used to designate the motion of light.Sometimes, light follows a random series of shorter and longer steps rather than travelling in a predictable Brownian diffusion. The shorter and longer steps together form a Lévy flights walk. Most of the natural search processes use Lévy flights. Some bee species perform Lévy flights to find the flowers in a new area. Survey says, by performing Levy flights more area can be covered than normal random search. Performing Levy flight is additionally informative than the traditional search methods. Lévy flight is defined by the **Eqn.5.19:**

$$x_i^{t+1} = x_i^t \alpha L(s, \lambda) \tag{5.19}$$

$L(s, \lambda) = \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda/2)}{\pi} \frac{1}{s^{1+\lambda}}$, $(s \gg s_0 > 0)$; $\alpha > 0$ is the step size scaling factor. (5.20)

In Lévy flights the Mantegna's algorithm is used to generate the step size for the determination of search space which is given by **Eqn. 5.21.**

$$s = \frac{U}{|V|^{1/\lambda}} \tag{5.21}$$

where U and V are the two Gaussian distributions and λ is the characteristic scale of the problem.

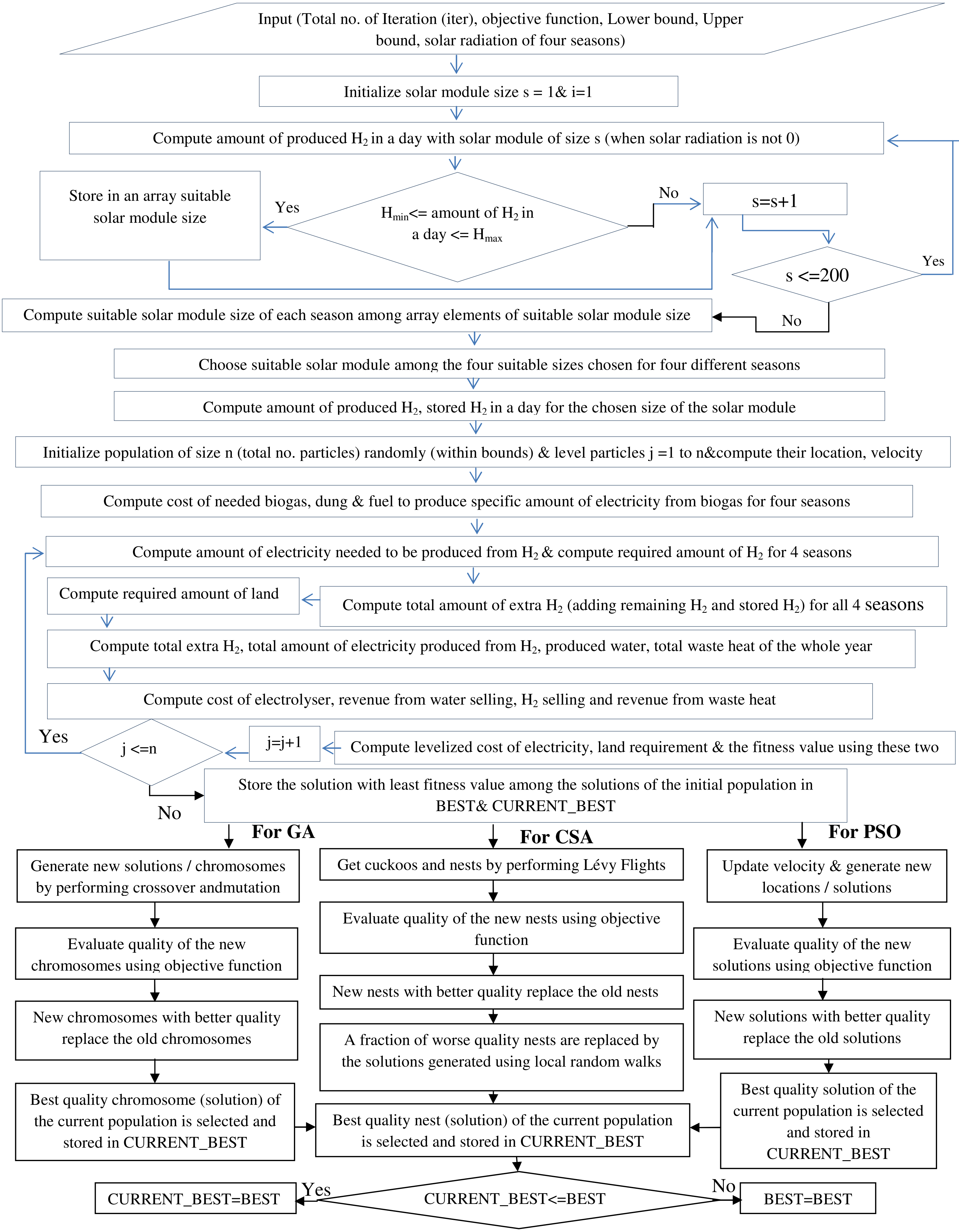


Figure 5.5: Flow chart of the optimization scheme using GA, PSO and CSA

5.2.6. Economic Modeling

An economic model is a simplified description of reality, designed to yield hypothesis about the economic behavior that can be tested (International Monetary Fund 2016). The economic model is essential to make the polygeneration socially acceptable to the villagers. The economic performance is assessed along with the thermodynamic performance of the system to judge the overall suitability of the system (Khalid et al. 2017). The various input data for economic modeling is shown in **Table 5.3.**

Table 5.3: Input values for economic calculation

Serial No	Name of component	Value
1	1 USD	60 INR
2	1 CHF	70.18 INR
3	Price of fuel cell per kW	55 USD (DOE 2016)
4	Solar Module price per watt	0.64 USD (US photovoltaic prices 2015)
5	Electrolyser capital cost per kW	1090 CHF (Parra and Patel 2016)
6	Cost of hydrogen storage per kg for metal hydride storage	1.68 USD (Balchandra and Reddy 2016)
8	Cost of hydrogen per kg	3.70 USD (NREL 2014)
9	Price of Solar module per watt with battery	1.64 USD
10	Utility heating price	0.013 USD/kWh (Jana and De 2015 d)
11	Cost of cattle dung	0.0033 USD/kg (Chauhan and Saini,2016)
12	Cost of waste heat recovery systems for heating utility per kW	1.66 USD
13	Plant life	25 years (Jana and De, 2015c)
14	Efficiency of PEM fuel cell	65% (Kreith and Krundeick 2015)
15	Efficiency of gas engine	27%(Chauhan and Saini 2016)
16	Efficiency of PEM electrolyzer	80%(Kreith and Krundeick 2015)
17	Efficiency of solar module	14%
18	Cost of wind turbine per kW	1450 USD(IRENA 2017)

19	Derating factor of PV modules	0.8**(NREL 2017)**
20	Bank discount rate	10%
21	Population of the village	400
22	Initial investment with SPV battery systems	640 USD
23	Calorific value of biogas	21 MJ/m^3**(Shane et al 2017)**

5.2.6.1. Cost of solar PV

The total cost of PV installation, CP_{total}l is given by**Eqn.5.22**

$$CP_{total} = CP_{sol} \times PV_{installed} \times 1000 \tag{5.22}$$

Where,$CP_{sol}$is the cost of PV module per watt at the peakof solar radiation and $PV_{installed}$ is the total installed capacity of the PV module.

5.2.6.2. Cost of Fuel cell

The total cost of fuel cell installation, $FC_{total}$is given by**Eqn.5.23**

$$CFC_{total} = CP_{fc} \times FC_{ins} \tag{5.23}$$

Where CP_{fc}isthe cost of fuel cell per watt and $FC_{ins}$is the total installed capacity of the fuel cell system.

5.2.6.3. Cost of biogas system

The cost of biogas systems does not increase linearly with scale. The cost of biogas system is given by the **Eqn. 5.24** (Jana and De 2015d)**.**

$$\mathrm{C_{eqb}} = C_{\mathrm{eqa}} \left(\frac{\mathrm{Capacity_b}}{\mathrm{Capacity_a}}\right)^{\mathrm{S}} \tag{5.24}$$

Where C_{eqb} is the cost of bio gas system of capacity 'b', the C_{eqa} is the cost of capacity of another biogas system 'a' and 's' is the scale factor for wet biomass systems.

5.2.6.4. Cost of electrolyzer

The initial cost of electrolyzer, CE_{total} is given by**Eqn.5.25.**

$$CE_{total} = CP_{elec} \times EL_{installed} \quad (5.25)$$

Where,$CP_{elec}$is the cost of electrolyzer per watt and $EL_{installed}$ is the installed capacity of the electrolyzer.

5.2.6.5. Cost of hydrogen storage

The cost of hydrogen storage CH_s is given by**Eqn.5.26**

$$CH_S = H_d \times H_{kg} \quad (5.26)$$

H_{kg} is the cost incurred to store 1 kg of hydrogen in metal hydride tank and H_d is the maximum hydrogen required per day to meet the night load in a particular season.

5.2.6.6. Cost of wind turbine

The cost of wind turbine CW_{total} is given by **Eqn.5.27**

$$CW_{total} = W_{installed} \times CW_{inperkW} \quad (5.27)$$

Where CW_{total} is the total initial investment for the installation of the wind turbine, $W_{installed}$ is the installation capacity of wind turbine and $CW_{inperkW}$ is the cost of installation of wind turbines per kW.

5.2.6.7.Cost of gaseous mixture

The cost of 1 kg of gaseous mixture, C_g, is given by **Eqn.5.28**

$$C_g = C_H \times \frac{CV_g}{CV_h} \tag{5.28}$$

Where, CV_g is the calorific value of the gaseous mixture and CV_h is the calorific value of hydrogen.

5.2.6.8. Annualized Initial Investment

The annualized initial investment (AI) is given by**Eqn.5.29**

$$AI = \{(CP_{total} + CFC_{total} + \mathrm{C}_{\mathrm{eqb}} + CE_{total} + CH_{\mathrm{s}} + CW_{total} + C_{eqbg} + C_{wh}) \times \mathrm{CRF}\} + CH_t \tag{5.29}$$

Where CP_{total} is the total installation cost of the PV module, CFC_{total} is the total cost of installation of the fuel cell, $\mathrm{C}_{\mathrm{eqb}}$is the total cost of installation of the biogas systems, CE_{total} is the total initial cost of the electrolyser, CH_S is the total initial cost of the hydrogen storage systems, CW_{total} is the total cost for wind turbine installation, C_{eqbg} is the initial cost for the biomass gasifier system C_{wh} is the intial cost of the waste heat recovery system and CRF if the capital recovery factor given by **Eqn. 5.30**

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5.30}$$

Where i is the discount rate and n is the economic life of the system. The economic lives of different components may be different and hence annualized cost is considered.

5.2.6.9. Annualized Revenue

The annualized revenue R_y is given by

$$R_y = R_G + R_{wh} \tag{5.31}$$

Where R_G is the revenue earned from selling gaseous mixture of high calorific value and R_{wh} is the revenue earned from utility heat.

5.2.6.10. Levelized cost of electricity (LCOE)

The LCOE is a convenient tool to assess the competitiveness of different generating technologies. The LCOE is calculated taking into consideration the capital cost, fuel cost, fixed and variable operations and maintenance cost (USEIA 2016)**.**The LCOE is given by **Eqn.5.32.**

$$LCOE = \frac{AI+CM+CF-R_y}{E_t} \tag{5.32}$$

Where AI is the annualized initial investment (i.e. capital cost), CM is the annualized maintenance cost, CF is the annualized fuel cost i.e. cost of cattle dung for the present system, $R_y$is the total revenue generated by selling utilities other than electricity. E_t is the total units of electricity generated per year. For renewable energy systems, the maintenance cost and the fuel cost is almost negligible with respect to the initial investment (Budischak et al. 2013). Hence, effects of these are neglected for this study.

5.2.7. Analysis of reliability of power supply

Reliability of electricity supply is an important aspect for the design of any renewable energy system. The analysis of reliability of power supply gives a quantitative idea of the amount of power failure for a renewable energy system. Reliability of power supply can be calculated in different ways. In this chapterthis is calculated using the Loss of Power Supply Probability method (LPSP) and Unmet Load (UL) probability method. The LPSP method takes into account both the magnitude of the power failure and the total hours of power failure as shown in **Eqn. 5.32.** The UL probability method takes into account only the hours of power failure as shown in **Eqn. 5.33**(Sinha and Chandel 2015)**.**

$$LPSP = \frac{\sum_{i=1}^{i=\mathrm{n}} E_{deficit}}{\sum_{i=1}^{i=N} P_{load}} \tag{5.33}$$

Where $E_{deficit}$ is the total electrical energy deficit per year and P_{load} is the total electrical energy required per year.

$$UL = \frac{\sum_{i=1}^{i=N} T_{failure}}{\sum_{i=1}^{i=N} T_{total}} \tag{5.34}$$

Where $T_{failure}$ is the total hours of electricity failure per year and T_{total} is the total hours of operation of the plant per year.

5.2.8. Objective function

The main objective of this work is to optimize the system to simultaneously minimize three required inputs as a combined one. These are LCOE (INR/kWh), land requirement (m^2) and GHG emission (g-CO_2 equivalent).All these inputs are combined into a single objective function for simultaneous optimization of this using weighted sum method.

The objective function is given by **Eqn. 5.35.**

$$S_{obj} = W_f \times \mathrm{NF}_{\mathrm{LCOE}} \times LCOE + W_L \times \mathrm{NF}_{\mathrm{L}} \times L + W_G \times \mathrm{NF}_{\mathrm{G}} \times G \tag{5.35}$$

Where W_f is the weighing factor for LCOE, W_L and $\mathrm{W_G}$are the same for land requirement and GHG emission respectively and $\mathrm{NF_{LCOE}}$, $\mathrm{NF_L}$ and$\mathrm{NF_G}$ are the normalization factors for LCOE, land requirement and GHG emission respectively to convert the values of each within an order of 10.The value of $\mathrm{NF_{LCOE}}, \mathrm{NF_L},$ and $\mathrm{NF_G}$ are $1, 10^{-3}$ and 10^{-1} respectively. Values of three weighing factors are given in **Table 5.4.** Values of these weighing factors are decided according to the “priority” of these three for optimization. Higher the priority of optimization, higher is the value of weighing factor. The constraints of optimization are given in **Table 5.4.**

Table 5.4: Constraints for optimization

Serial No	**Parameter**	**Value**
1	Weighing factor for LCOE (W_f)	0.6
2	Weighing factor for land requirement (W_l)	0.2
3	Weighing factor for GHG emission (W_G)	0.2
4	Reliability of power supply	100%
5	Daily availability of biogas	728m^3/day
6	Yearly availability of biomass	108 tons/year
7	Betz limit	0.59
8	Constant heating load	2 kW

5.3. Results and discussions

In this chapter, optimized capacities of the various components of the polygeneration system are shown in Table 5.5, which is determined by the multi objective optimization by a program developed in MATLAB 2013. Objective of this optimization is simultaneous minimization of LCOE, land requirement and GHG emission using CSA.

Table 5.5: Optimized capacity of the components

Serial No	Name of component	Size
1	Photovoltaic module	120.11 kW
2	Wind turbine	3.745 kW
3	Fuel Cell	57.213 kW
4	Gas Engine	1 kW
5	Land required	3654 m^2

6	Size of biogas digester	800 m^3/day
7	Size of biomass gasifier	41.27 kW_e
8	Size of metal hydride storage tank	2.5kg/day
9	Size of the electrolyzer	100 kW

In the present study, a polygeneration system has been proposed with PV module, wind turbine, PEM electrolyzer, PEM fuel cell, metal hydride tank, biogas digester and biomass gasifier. Electricity is the principal output. The other utility outputs are heat andgaseous mixture of hydrogen and biogas with high CV. Decentralized generation using the renewable sources of energy may be a good option for rural electrification of India. Moreover, electricity is not the only need of the villagers. Apart from the electricity, the people in the villages also need other utilities, say, cooking fuel, utility heating etc. So if more utilities are obtained from a single efficiently integrated unit and catering to the needs of local people it will be even more beneficial for the villagers. With revenue earned through more utilities LCOE decreases. Hence the efficient integration of several processes through polygeneration decreases the LCOE. Effects of the system integration on LCOE are studied in this section.

In the present study, it is observed that the revenue shares of electricity and gas are nearly equal as shown in **Figure5.6**.

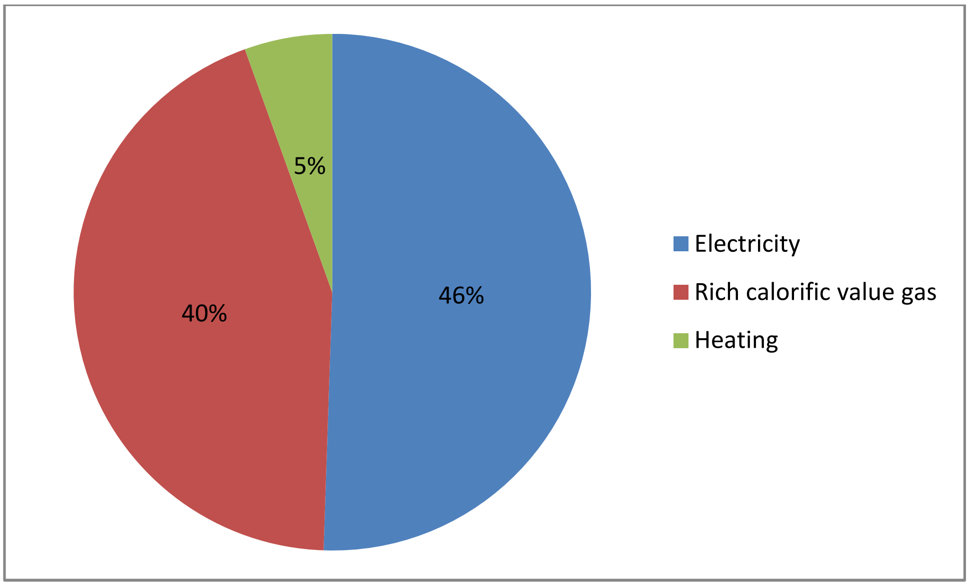


Figure5.6: Pie chart showing the percentage share of annualized income from selling different utilitie*s*

The simultaneous production of electricity and hydrogen from the same system helps to accommodate the variation in the load curve of this particular location. When there is excess (i.e. the surplus electricity after meeting the instantaneous load) electricity (i.e. the surplus electricity after meeting the instantaneous load) it is diverted towards hydrogen production through electrolysis of water which is a clean fuel with high calorific value. The hydrogen is mixed with the biogas to yield a rich calorific value gas used for cooking and electricity generation purpose. The surplus of this gas is sold out generating revenue. In the present study, the LCOE is the principal indicator of the economic performance of the polygeneration plant. So,effects of changing various parameters on LCOE is to be studied to assess the suitability of the plant in the long run from the economic point of view. This also helps to identify the principal factors affecting the economic performance of the plant. The effects of various parameters on LCOE are shown in **Figure 5.7(a)-7(h).**The various parameters for sensitivity analysis is given in **Table 5.6**.

Table 5.6: Variations considered for sensitivity analysis for variation of LCOE

Serial No	Parameter	Range
1	Life of the polygeneration plant	5 years to 30 years
2	Percentage of supply of excess biogas	0-100
3	Different types of hybridization	---------
4	Addition of different utilities	----------
5	Application of different optimization algorithms	------------
6	Percentage of increase in initial investment	---------------
7	Reliability of power supply	0-100

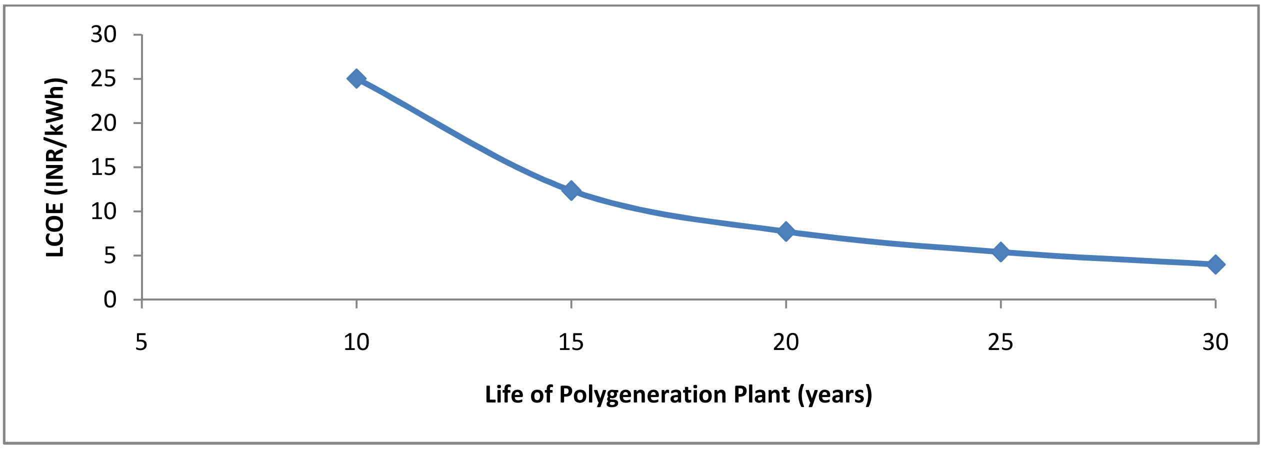


Figure5.7 (a): Variation of LCOE with life of the plant

Figure 5.7(a) shows the variation of LCOE with the life of the polygeneration plant. The LCOE is high if the life of the plant is below 15 years and it increases rapidly with decreasing plant life. Higher life time of the plant i.e. more than 15 years decreases the LCOE at a lesser rateand the LCOE is almost constant if the plant life is above 20 years. So for the better economic operation of the plant the life of the plant should be 20 years or more.

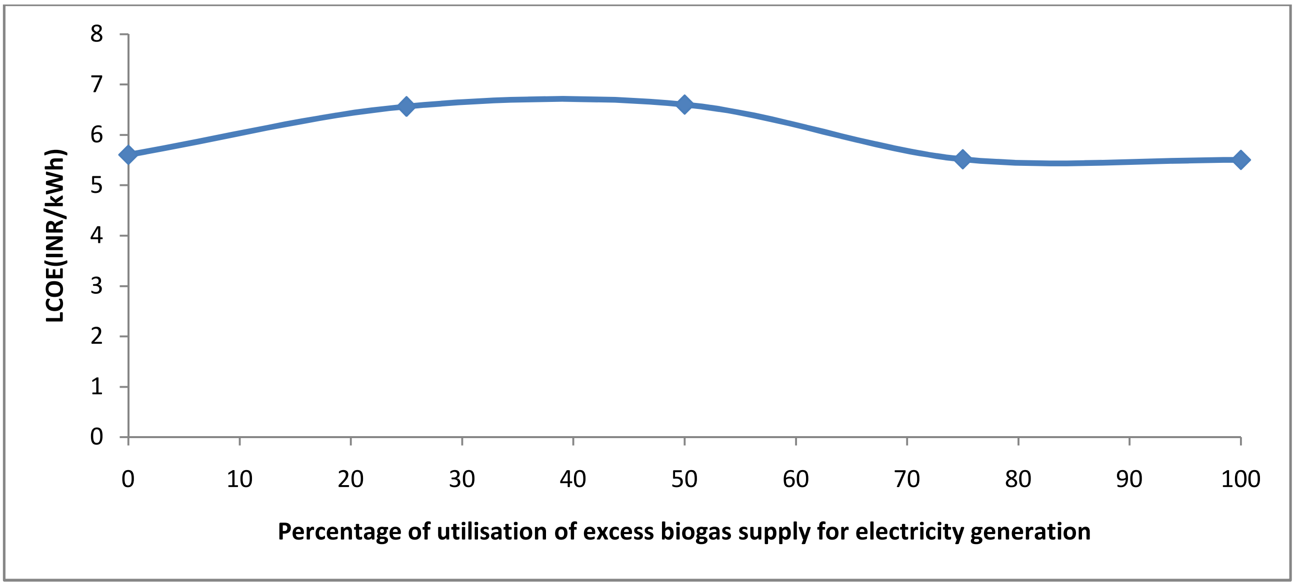


Figure5.7 (b): Variation of LCOE with percentage of excess biogas utilization

In India above 90% of the rural households use firewood as the cooking fuel. Firewood does not burn properly in a conventional way. Rampant use of the firewood for cooking also leads to deforestation causing environmental damages. At the same time, in most of the villages plenty of cattle are available. The cattle dung has a good potential of biogas production. The biogas can be mixed with hydrogen for increasing its calorific value. This high calorific value gaseous mixture can be used as a better cooking fuel. In the present study, about 65% of the total produced gaseous mixture can be used for the electricity generation which is the surplus amount after cooking requirement of the village. This amount of gaseous mixtureis termed as 'excess' gas in **Figure 5.7(b)**.

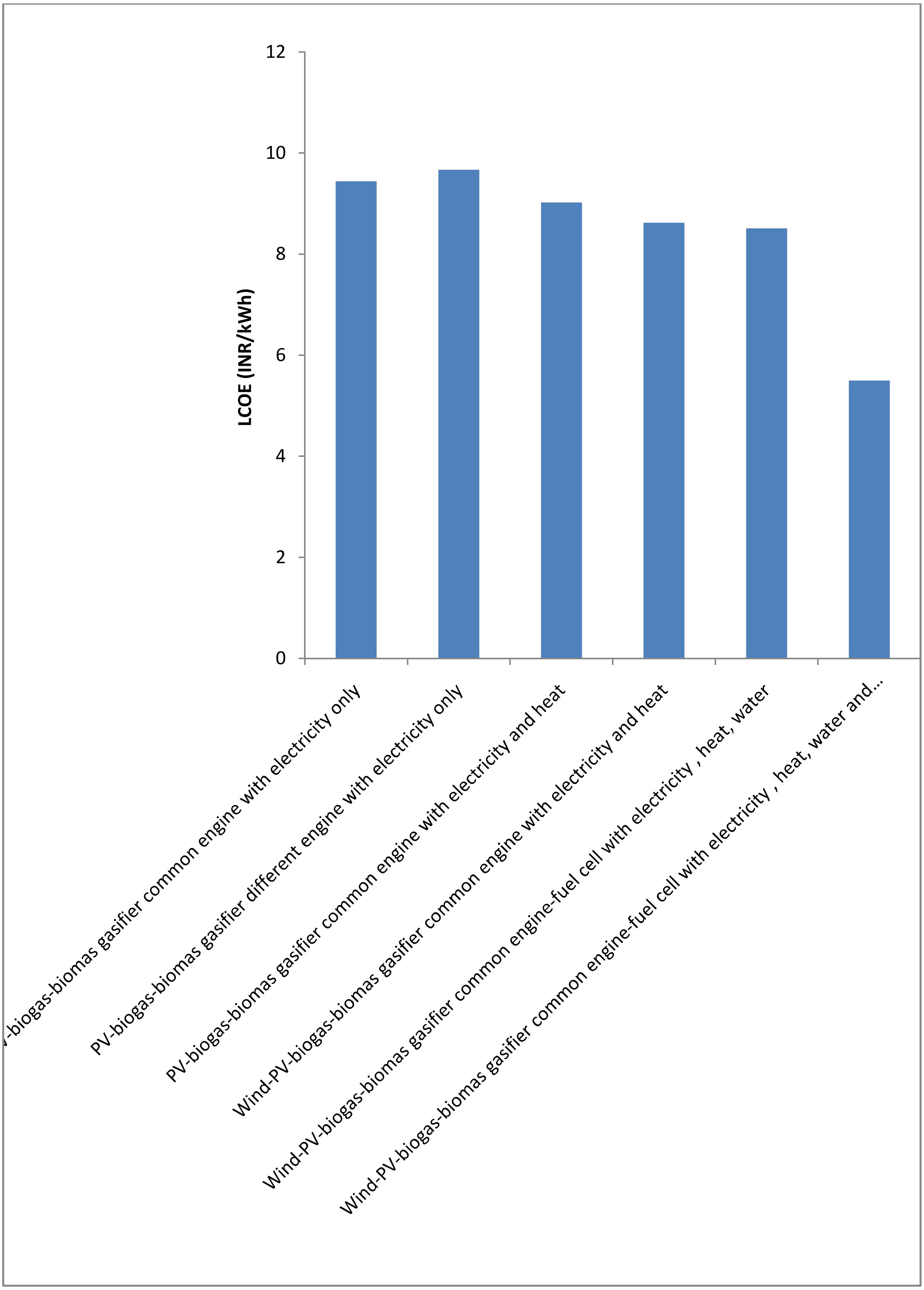


Figure5.7 (c): Variation of LCOE with hybridization of various renewable energy sources

Cooking need has more priority than electricity in the villages. Moreover, the biogas production may also vary due to many reasons. If the percentage of use of the gas for electricity generation drops below 60%, then there is an increase in LCOE. This is due to non-utilization of the total capacity of the biogas digester. Moreover, this will lead to increase in size of the fuel cell and wind turbine systems. Hence, the LCOE increases.The renewable sources of energy generally are intermittent in nature. The resources are not available as per the human need with time i.e. following the load curve. To get reliable power supply using the renewable sources of energy there are two options. These are either storage and/or hybridization. Most common storage option is to store electricity in a battery. On the other hand, hybridization means to integrate two or more sources of renewable energies like solar, biomass, wind etc.to deliver electricity. **Figure5.7(c)** shows the variation of LCOE with hybridization of the various sources. Bar chart in **Figure 5.7(c)** shows the LCOE for only electricity generation (i.e. without other utilities) using different possible combinations from solar-PV battery option and subsequently combining with other possible options. Here battery indicates storage and other adding options without battery indicate more hybridization. Combinations are plotted from maximum to minimum LCOE. The results of this study show that more hybridization combinations are plotted for maximum to minimum LCOE. The LCOE is the highest for a PV-battery storage system. The LCOE decreases with more hybridization. The least LCOE is obtained when Wind-PV-Fuel cell-gasifier-biogas digester i.e. almost all the available renewable energy sources considered for this study are hybridized. The variation of the sizes of the different components like solar PV module, wind turbine etc with different hybridizations is shown in **Table 5.7.**

Table 5.7: The change of the capacity of the electricity generators on hybridization with other generators

Possible combinations of hybridization	**Photovoltaic Module (kW)**	**Biomass gasifier (kW_e)**	**Biogas digester (m^3/day)**	**Wind turbine (kW)**	**Fuel cell (kW)**
PV module with battery	400	0	0	0	0
PV module with wind turbine with battery	325	0	0	15	0
PV-Gasifier	325	70	0	0	0
Wind-PV-Gasifier	318	68	0	10	0
Wind-PV-Gasifier-Fuel cell	200	55.43	0	7.5	0
Wind-PV-Gasifier-Fuel cell-biogas digester	120	41.25	800	3.75	58

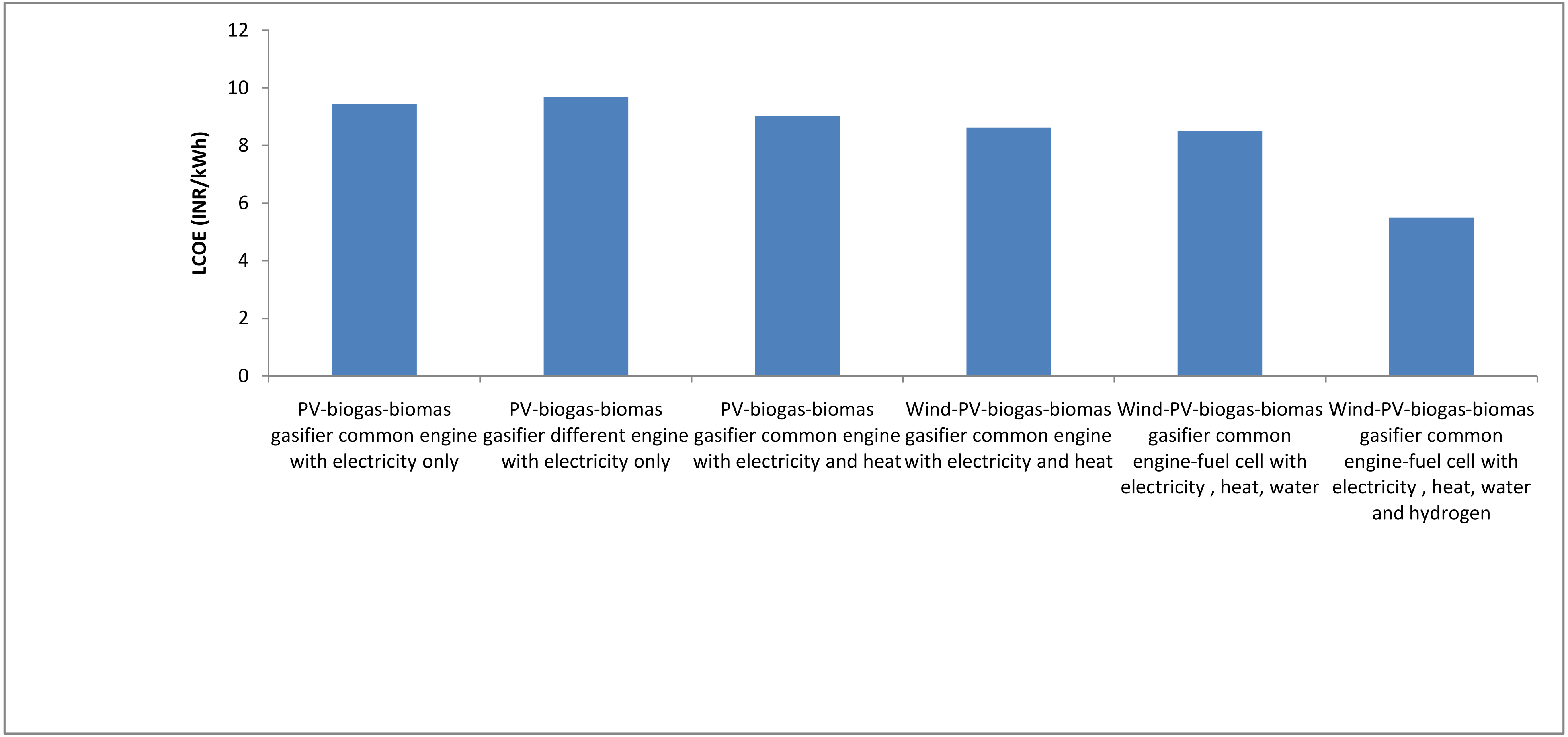


Figure 5.7(d): Adding of different utilities

In a polygeneration system, multiple utility outputs are obtained from the same integrated system. Other utilities in addition to electricity are then integrated to study the effect of such integrated system on LCOE in **Figure 5.7(d)**. **Figure 5.7(d)** shows that the LCOE decreases with adding up of more utilities along with electricity and better process integration. The LCOE is highest for a PV-battery system when the utility output is only electricity with no hybridization. The LCOE decreases to some extent when PV is hybridized with wind. In Wind-PV-Gasifier system, there are two utilities i.e. electricity and waste heat. In this case the LCOE has even decreased more.

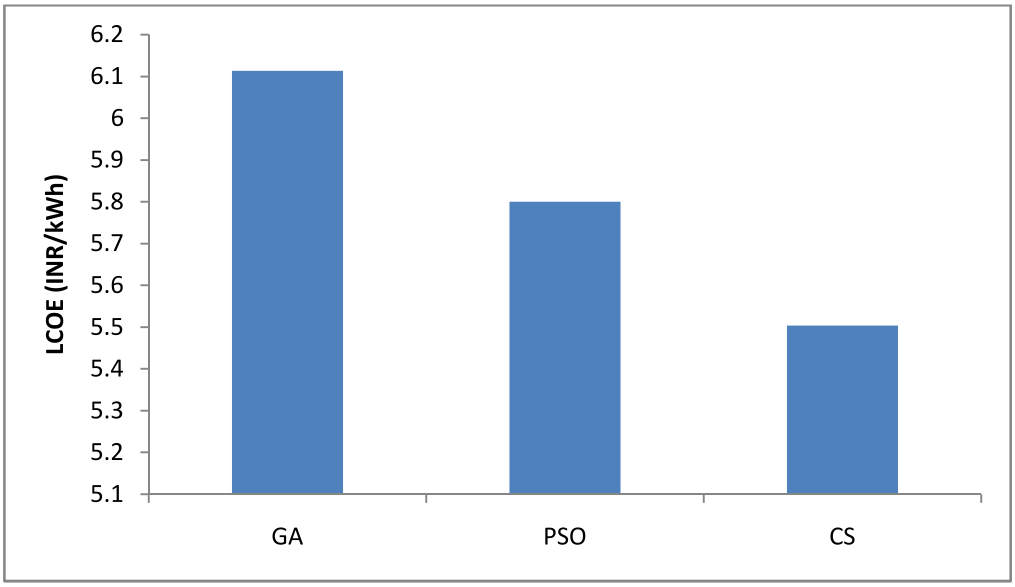


***Figure5.7 (e):** Variation of LCOE with Different algorithms*

Figure 5.7(e) shows the different optimized LCOE for different algorithms (like GA, PSO) after forty iterations. The cuckoo search gives the best results because of the global random walks generated by the Levy flights. Moreover unlike the other algorithms, the CS performs the global convergence whereas the other algorithms find out the current best solution. For the multi modal optimization, the other algorithms converge to the current best solution without going for the global best solution for a definite search space.

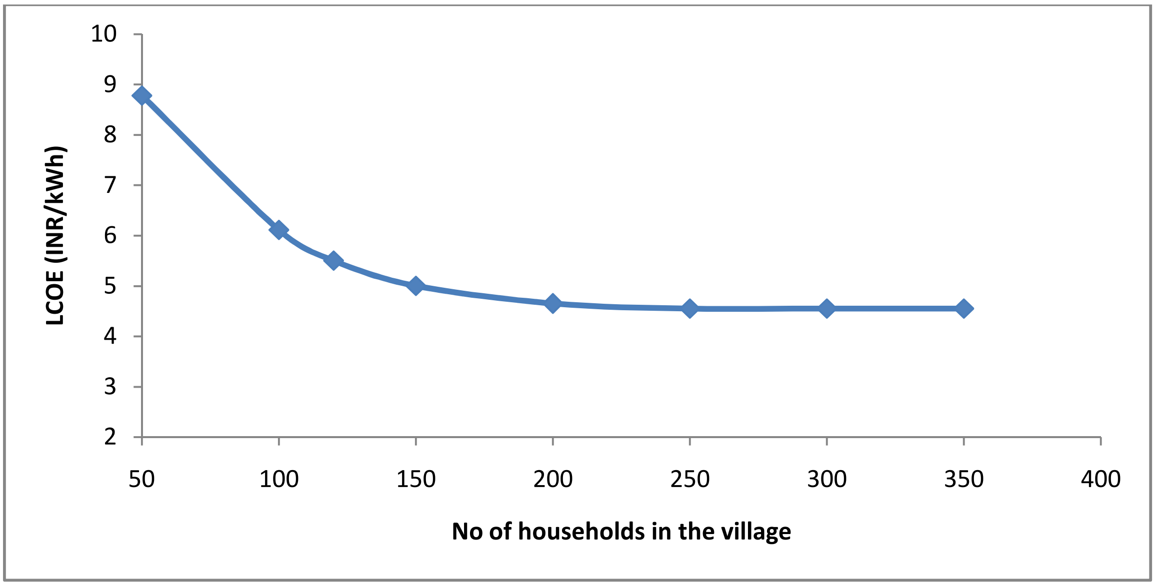


Figure5.7 (f): Variation of LCOE with number of households

It is necessary to study the suitability of a renewable energy system with respect to the population size of an area. The design of a renewable energy system depends on the number of consumers. The number of consumers generally increases with the number of the households. Hence the number of households in a village may serve as an indicator of the population. In the present study, the assumed population of the village is 400 persons and the number of households is assumed to be 100. **Figure 5.7(f)** shows the variation of LCOE with the number of households. It is found that for the economic operation of the plant the number of households must be greater than one hundred and fifty. So the increase in the number of households leads to the decrease in LCOE. Moreover, the capacity utilization of the individual renewable energy devices will also increase. In this study, it is seen that the LCOE decreases if the population in a certain area increases.

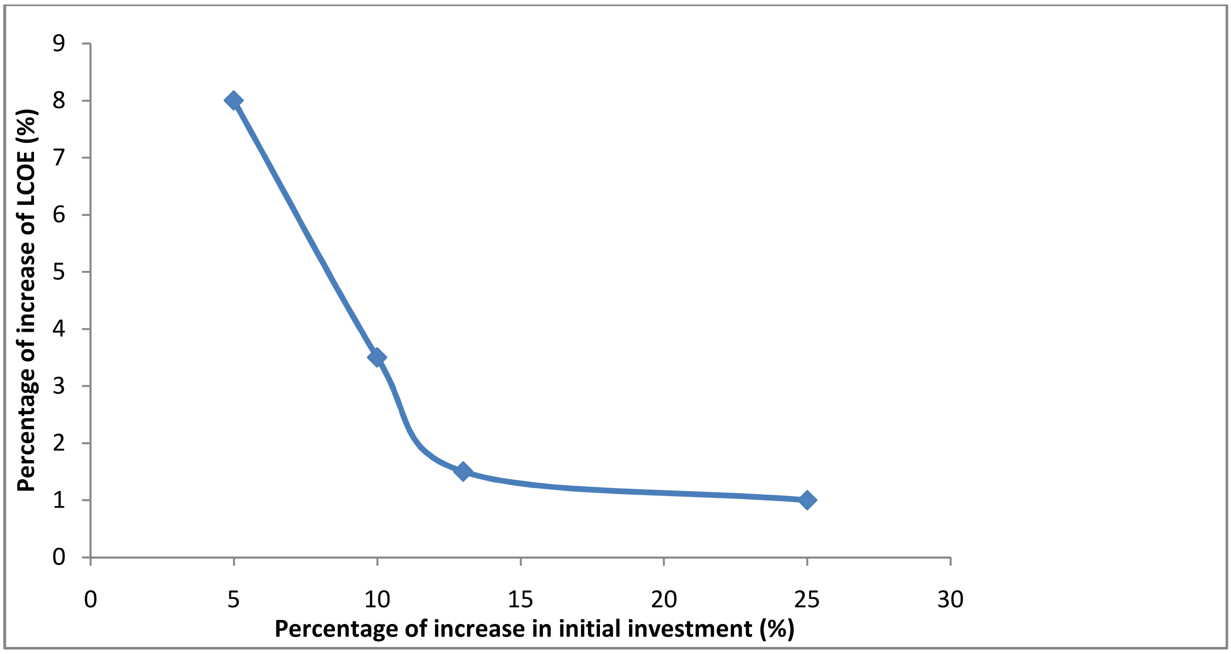


Figure5.7 (g): Variation of LCOE with Percentage of increase in initial investment

Figure 5.7(g) shows the percentage of increase in LCOE with the increase in initial investment. Electrification of this area with the PV-battery systems is considered as the base for comparing the other optimized hybridized multi-generation system. Renewable energy resources are intermittent in nature. Hence to get uninterrupted power supply hybridization of one or more renewable resources is necessary. The inclusion of more types of renewable energy generators (like SPV, wind turbine etc) increases the initial capital investment. It has been observed that when the percentage of increase in the initial investment is 15% then the LCOE is decreased by 4%. This area signifies the inclusion of the wind turbine. The initial investment increases with the incorporation of the wind turbine but the LCOE decreases. There is a sharp decrease in LCOE (nearly 9%) when there is a 25% increase in the initial investment. The rise in the initial investment is due to the incorporation of the hydrogen based systems like PEM electrolyzer and PEM fuel cell. The LCOE decreases as the excess hydrogen mixed with biogas is sold with a good market price. Thus, hybridization can be viewed as a more efficient way of insitu resource utilization.

Reliability of power supply means assured continuity of power supply without failure. Thus higher the value of reliability of power supply lower is the chance of power failure. The renewable energy systems are intermittent in nature. These energy can be generated when the resources are available but not when it is actually needed. This is one of the most important issues to address for renewable energy introduction replacing the fossil fuel options. So effect of the reliability of power supply on LCOE is studied here. The reliability of power supply is calculated both by "Loss of Power Supply Probability" and "Unmet load" method as shown in **Eqn. 5.33 and Eqn. 5.34**respectively. **Figure5.7(h)** shows that the increase in reliability of above 40% decreases the LCOE.

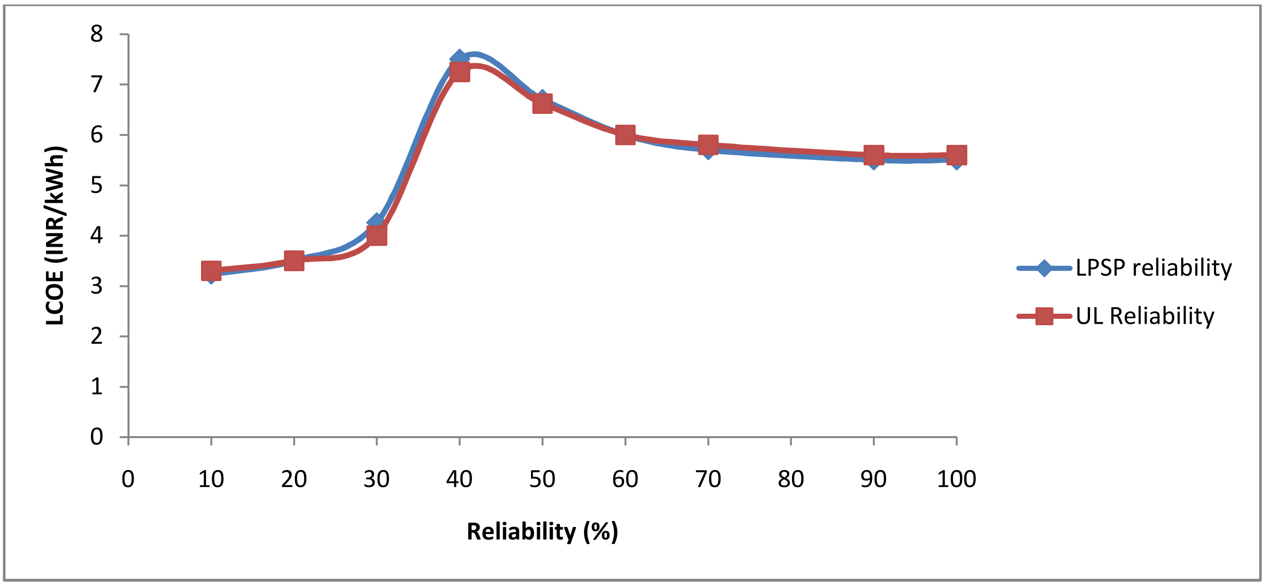


Figure 5.7 (h): Reliability of power supply

This is also a socially acceptable solution. This is because for the renewable energy systems the running cost is negligible with respect to the initial cost. During the load shedding hours no revenue is generated but the initial investment is already done. Hence the LCOE decreases. As reliable uninterrupted power supply assures better social as well as economic solutions, 100% reliability of supply (i.e. no power failure) is considered as the constraint for this optimization.

The unit prices of components may vary due to many technical as well as socio economic factors. So to study the suitability of the system in the varying price environment the sensitivity analysis is carried out by varying the price of each of the components of the polygeneration system i.e. solar module, wind turbine and the fuel cell as shown in **Figure5.8.**

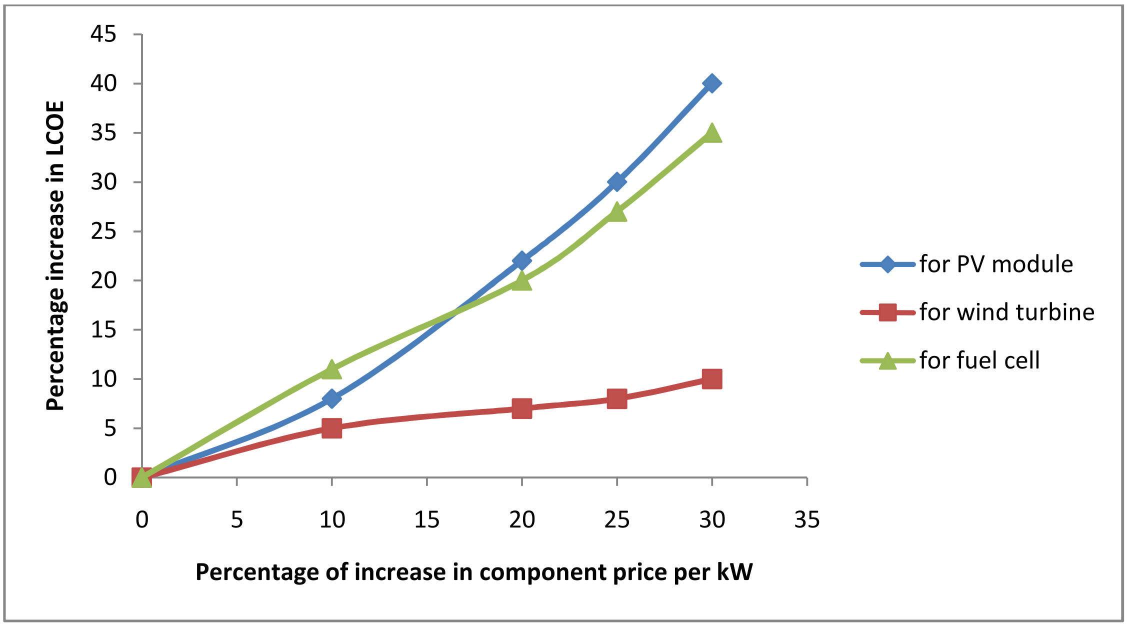


Figure 5.8: Variation of percentage of increase in LCOE with the percentage increase in per kW price of the components

Here the price of each of the components is varied within a range of 30% of the base price. The present base price of all these components is shown in **Table 5.3. In Figure5.8,** it is observed that the percentage of increase in LCOE is most steep with the rise in the cost of PV module per kW. This is because PV is the principal generator of electricity in this polygeneration system. Moreover the electricity from PV in excess to that for local consumption also generates hydrogen through electrolysis. Hydrogen is mixed with the biogas to form gaseous mixture with high CV. This lowers the LCOE. But if the unit cost of PV module per kW increases then the hydrogen generation also becomes more costly. This also has a positive effect on the rise of LCOE. Next to PV, the LCOE is sensitive to rise in fuel cell prices per kW. This affects as the unit cost of fuel cell is high and it is the second largest electricity producer in this polygeneration system. The LCOE is least affected by the increase in per kW price of wind turbine. This is because the optimized size of wind turbine is much smaller than the other two. The locally available wind resource is also much less than the solar resource. Hence the size of the wind turbine is relatively smaller.

In this study, a multi-objective optimization is carried out considering the minimization of LCOE, land requirement and GHG emission. In this study LCOE is given the maximum weightage. **Figure5.9** shows the effect of LCOE if the other factors like land requirement and GHG emission are given topmost priority i.e. the LCOE at least land requirement and least GHG emission are shown.

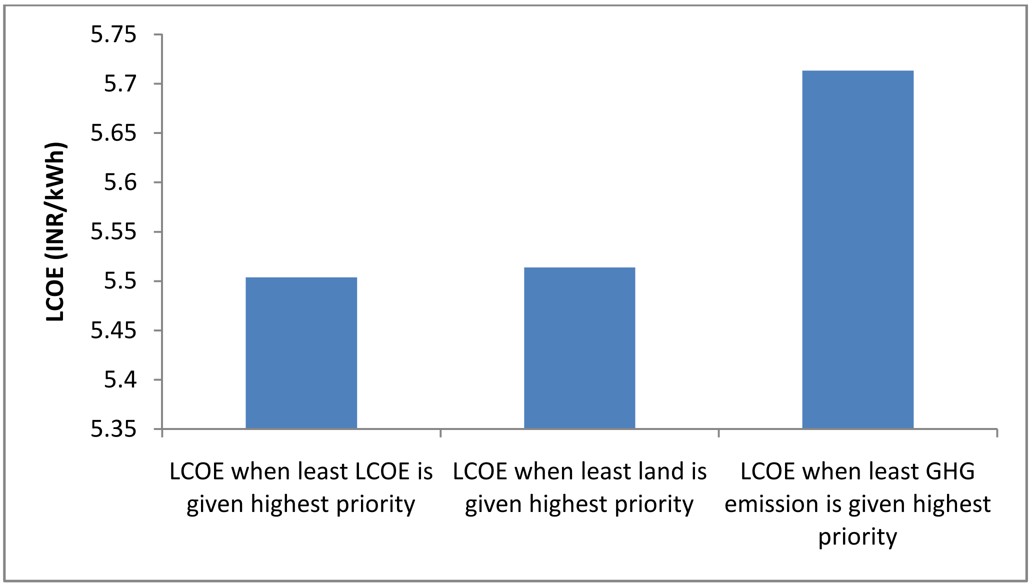


Figure 5.9: LCOE with different weightage factors to different factors

In this study **Fig 5.10** shows the pareto optimal front. The objective functions are the cost and land requirement. Here, both the objective functions are decreasing. So, the points on the graph show the non dominated solutions which are basically the optimized results.

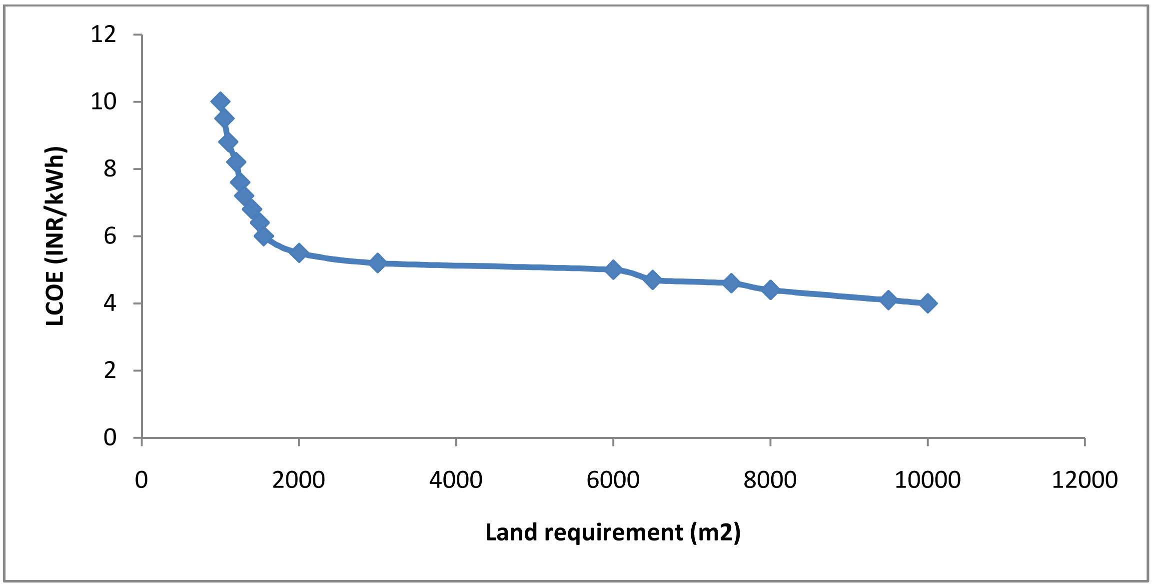


Figure 5.10: Pareto Optimal Front

5.4. Conclusion

The extension of national grid across the whole country is difficult due to the terrain conditions and other socio economic problems of India. In this context decentralized generation using locally available resources may provide a solution for the electrification of these scattered hamlets. A system is analyzed in this study with solar PV module, wind turbine, PEM electrolyzer, PEM fuel cell, metal hydride tank, biogas digester (using cattle dung) and biomass (straw) gasifier. Here the suitable sizes of the components are determined using Cuckoo Search Algorithm for optimum economic operation, land use and GHG emission.

Electricity is not the only utility need of the local villagers. In this study,it is observed that if some other utilities can be integrated with the electricity generation through efficient process integration, the overall system performance improves. Addition of economic values to these utilities leads to economic benefit thereby lowering LCOE. Thus polygeneration beneficially integrates generation of other utility outputs along with electricity. The LCOE lowers when the plant life is above 15 years. The LCOE decreases with hybridization and the addition of other utility outputs. The LCOE also decreases with the increase of reliability of the power supply above 50% which is a better socially acceptable solution too.

Methodology of this study is generic for multi criteria optimization with decided priority. However, data used is site specific and results obtained representing optimized solutions may vary both with data used as well as priority decided.

6. Techno-economic optimization of a small scale distributed polygeneration with local renewable resources for a remote place of India

6.1. Introduction

Energy is the key factor for economic development (Carley et al, 2011)**.**Consumption of energy and gross domestic product (GDP) is related to each other (Huang et al, 2008). Assured supply of electricity is critical for industrial growth of a nation. Presently global energy demand is mostly supplied by fossil fuel (mostly coal) based power plants (Hammond et al, 2008). However, fossil fuel reserves are fast depleting and green house gas emission (GHG) from these power plants also adds to the climate change problem(EIA, 2017)**.**To find alternative sources of energy is a critical challenge now. Renewable energy is virtually inexhaustible and generally with low GHG emission. Though renewable energy is only possible option for future, current state of the technology is not suitable to meet the global energy demand. Also intermittency and available limited local resources at a particular time and location is another serious limitation of renewable resources. Hence, meeting variable energy demand over a day in different seasons with renewable resources is even more difficult.

Decentralized energy solution using local renewable resources is an emerging sustainable option. Though electricity is the most basic energy need, several other energy services are generally required for any location. Integrating several energy services efficiently in a single unit called polygeneration is an advanced option for a better sustainable solution with improved efficiency and environmental performance even at a lower cost, Thus for a polygeneration both inputs and outputs may be multiple and proper selection of these will be based on availability of local demands and availability of resources.

In addition to technological limitations, socio-economic conditions have several implications on energy utilization at a particular location (Kanagawa and Nakata, 2008).Thus sustainable energy option for a locality depend not only on the new technology development but also finding innovative solution for economic and social issues on a case to case basis. In the eastern part of India, “Sunderban” is a world heritage site with widely varying bio diversity. This is a place with many small islands in the delta of the river Ganga. The place is also famous for dense forests with tiger reserves. However, available water here is mostly saline and hence opportunity for agriculture is also limited. Population here is generally very poor with severe constraints for economic activity, even agriculture. There is no grid power available to this place as it is not economical for this remote place and people here can neither afford such power. As a result no activity is virtually possible in this place after the sunset and there exists perpetual poverty. A possible energy solution for these people is distributed generation utilizing local renewable resources. The general quality of life of these poor people may improve significantly using such distributed renewable power. However, to compensate limited local resources and intermittency of these resources, hybridization of different renewable resources will be better solution (Williams et al, 1995).These people are even deprived of basic needs like drinking water. Non availability of minimum refrigerated storage compels these people to sale their agricultural products at a very cheap price. Providing community refrigeration may be useful for social and economic development of these people. Utilizing locally available biomass resources in addition to solar and wind resources will help to meet variable energy demand. Excess biomass after meeting the electricity demand may be utilized for ethanol production that may either be used for local land and river transport or may be sold in the local market to earn revenue. Integrating multiple available renewable resources as inputs and several utility outputs in a efficiently integrated single system is called polygeneration. Developing efficient polygeneration as small scale distributed energy solution will not only provide better energy solution to these people but also meet several other basic needs as well as add to the socio economic development of these people (Ray et al, 2017, Jana and De, 2017).Polygeneration is a better solution for high energy efficiency, low production cost and emission compared to the stand alone systems (Wang et al, 2017).

Optimized solution with suitable combination of different renewable resources to meet the need of the local people is a critical challenge for such systems to be practically feasible. Moreover, polygeneration or multi generation may be viewed as an efficient means of process integration and intensification. The efficient process integration and process intensification has proved beneficial in terms of increased energy efficiency and reduced GHG emission (Klemes and Varbonov, 2013). To design the multi-input and multi-output system, application of optimization algorithms is useful in order to improve the economic performance of the polygeneration. For designing polygeneration systems, both mixed integer linear programming and mixed integer programming are reported in literature (Jana et al, 2017). The application of suitable algorithms proves to be beneficial from the design and operation viewpoints. The optimization of polygeneration systems may be a single objective or multi-objective problem. The assessment of the performance of polygeneration may be with different objectives like thermodynamic, economic, environmental or combination of these (Ganagadharan et al, 2012). Both the single objective and the multi objective algorithms are used for the optimization of the polygeneration systems depending on the objective functions and the assessment procedure (Cortes-Fuentes et al, 2016). Ubando et al (Ubando et al, 2014) designed a bioenergy based polygeneration using fuzzy mixed integer linear programming. The results of the study show that there is negative carbon footprint in this system. Khan et al carried out a biogas based polygeneration system in Bangladesh delivering electricity, cooking gas and safe drinking water as output utilities. The system gave better economic performance than other available technologies for that particular location (Khan et al, 2014)**.** Sy et al (Sy et al, 2016) performed the target oriented robust optimization for optimal size determination of the components of a polygeneration system. The optimization showed improvement in the economic performance of the polygeneration plant .Illanes-Leiva et al. (Illavenes-Leiva et al, 2017) designed solar based polygeneration plant delivering, electricity, fresh water, heating and cooling as the utility outputs. It is observed that this polygeneration plant is cost effective and efficient if it lies in proximity to the consumption centers. The bio inspired algorithms like particle swarm optimization, evolutionary algorithm are used for the design of renewable based polygeneration systems (Sigarchin et al, 2016). These intelligent search techniques is found to be better in terms of computational simplicity when implemented for the design of distributed energy systems with electricity as the only output (Abmouleh et al, 2017). The use of cuckoo search algorithm in the design of the hybrid decentralized energy system is reported in literature (Singh and Fernandez, 2018). But the use of the quantum inspired metaheuristic algorithms for the design of the polygeneration systems is not much reported in literature.

From literature it is noted that small scale polygenaration using local renewable resources appears to be a future sustainable solution. However, optimization of such systems has to be done on a case to case basis depending on both the constraints of optimization as well as decided objective function .India has several remote places where electricity availability through grid may not be economically feasible and affordable too by the local poor people. Energy security of these places may be achieved through utilization of locally available renewable resources at a possible minimum cost. To meet the demand in a decentralized manner hybridization of different available resources is a possible option. To satisfy uninterrupted power supply at a minimum cost utilizing several renewable resources, optimization of sizes of different equipment is a technical challenge. Out of different optimization techniques Quantum Inspired Metaheuristic Algorithm may be explored to find a suitable optimized solution for this problem. A comparison of optimization results using several other bio inspired techniques will also be needful to explore suitable optimization tool for its purpose.

In this chapter, a techno-economic analysis has been presented for a distributed small scale polygeneration utilizing local renewable resources suitable for remote Sunderban location of India. To optimize intermittent availability of renewable resources to meet varying local demand, four renewable resources are combined as inputs to this polygeneration. These are solar (through photovoltaic), wind, straw from paddy field and animal waste. Outputs are electricity, community cooling service at moderate temperature, potable water and ethanol. For such small scale distributed polygeneration optimization is critical both with respect to varying load and available resources over the day. The capacity of different components utilizing locally available renewable resources in a mixed hybrid mode is optimized for minimum levelized cost of electricity (LCOE) through determination of optimum sizes of these devices.

6.2. Materials and methods

In this paper a polygeneration system has been analyzed for Sunderban area of India to meet the needs of the local villagers. The schematic of polygeneration is shown in **Fig 6.1**. This area is a deltaic area lying scattered by tidal creeks (Sunderbans, 2017). This area is also sparsely populated by poor people. So grid extension to this place is not feasible from economic view point. Population of this area is generally very poor. Limited agriculture is the main livelihood of the people of this region. Rice is one of the important crops here. The polygeneration system is developed utilizing the excess rice straw i.e. the straw which remains excess after feeding the cattle. Straw is a byproduct of this rice production. The straw to electricity also proves to be environmentally beneficial than straw to soil (Wiloso et al, 2014). In this polygeneration wind turbine (WT) and solar photovoltaic (PV) modules are used to produce power. This area has an adverse terrain scattered by creeks. So transportation of the fuels like petrol, diesel etc is difficult here. So, ethanol may be locally produced as a utility output. This ethanol may be used as the transportation fuel. Ethanol is also cleaner fuel than diesel or petrol (California Energy Commission, 2006). Hence the excess syngas produced by the gasifier which is not used to produce electricity to meet the local demand is fed to the ethanol producing units. The main livelihood of the people of this area is agriculture. So, cooling is a required utility for temporary storage of the agro based products for local consumption as well as for selling in open market. The cooling is done by a vapor absorption chiller running on the waste heat of the gas engine coupled with the biomass gasifier. This area is very near to the sea and there is severe scarcity of fresh water (Lakshmi and Rajagopalan, 2000).

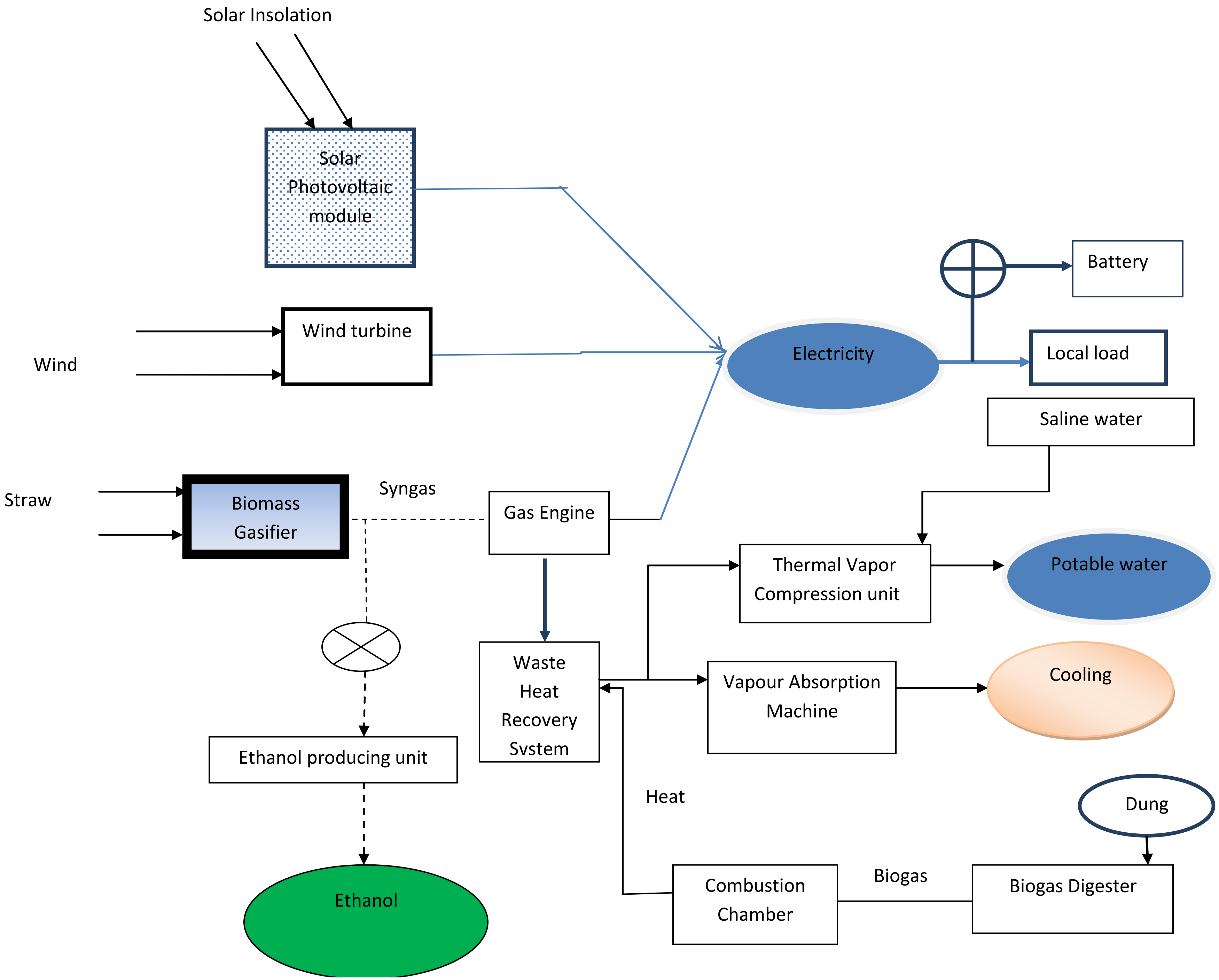


Fig 6.1: Schematic of polygeneration system

The potable water produced from saline river water as one of the utilities of this polygeneration system can be used for local consumption as drinking water. The allocated amount of drinking water is assumed to be 3liters per person per day (PHED, 2017). The waste heat of the gas engine and the heat produced by the combustion of biogas are fed to a thermal vapor compression (TVC) unit. Brackish water is fed to the TVC unit to produce fresh water. In this area, plenty of cattle are reared by the villagers. Cattle dung is collected from the households to feed the biogas digester to produce biogas. The mathematical model is developed using MATLAB 2013a in a computer with i3 processor. The optimization algorithm is also coded in MATLAB 2013a.

6.2.1 Modeling of solar PV system

With incidentsolar radiation on the module and it generates power as shown (in kW) in **Eqn 6.1**(Williams et al, 1995). The seasonal variation of the solar radiation is shown in **Fig 6.2.** The hourly solar radiation data is obtained from the National Renewable Energy Laboratory (NREL) website (India Solar Resource Map, 2017). The module is placed facing due south in order to generate maximum power for a given radiation is given in **Eqn 6.1** (Ray et al, 2017).

$$P_{solar}(k) = \frac{PV(m) \times R(t)}{s(t)} \tag{6.1}$$

Where $P_{solar}(k)$ is the power output of the module at k^{th} instant, PV (m) is the power output of the module at radiation of 1000 W/m^2,R (t) is radiation at t^{th} instant and $s(t)$ is the radiation of standard test condition which is equal to 1000 W/m^2. In this study only the beam radiation has been considered. This has been done as the amount of diffused radiation is less for this particular area. So, it has very less effect on the power output of the module.

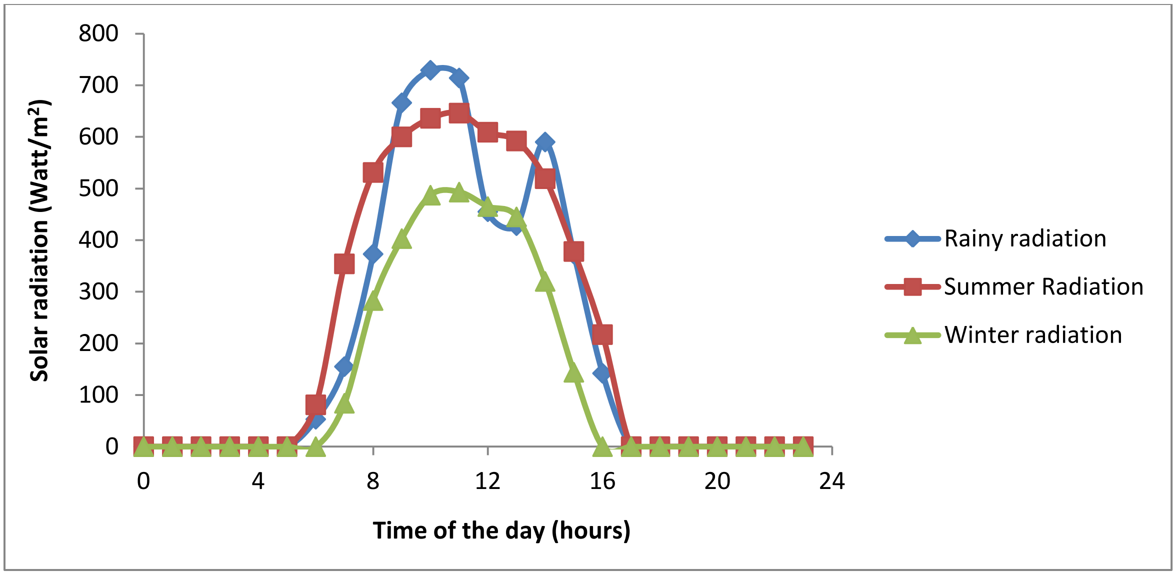


Fig 6.2: Solar radiation pattern in various seasons in Sunderban area **(India Solar Resource Map, 2017)**

6.2.2 Modeling of wind turbine

The power generated by the wind turbine P_{wind} is given by **Eqn6. 2**

$$P_{wind}(t) = 0.5 \times A \times \sigma \times v\ (t)^3 \times C_p \tag{6.2}$$

Where A is the swept area of the wind turbine, σ is the wind density, v (t) is the velocity of the wind and C_p is the fraction of power extracted from wind turbine..The wind speed data is taken from NASA meteorological website as shown in **Fig 6.3(NASA, 2017)**.

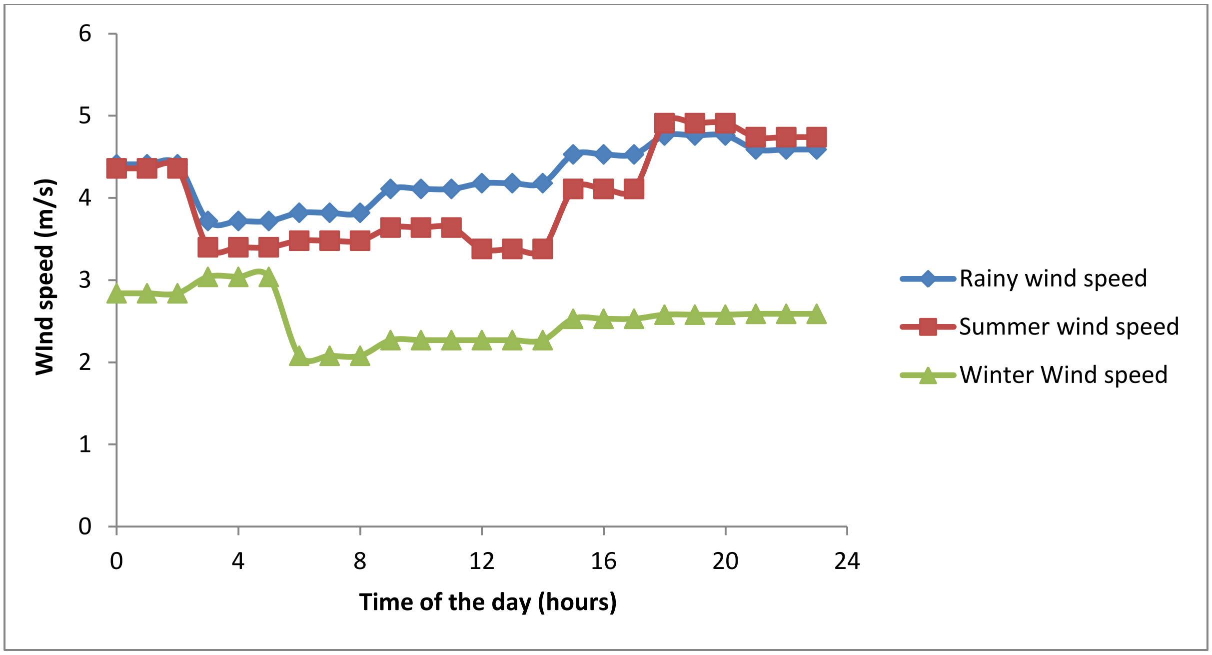


Fig 6.3: Wind speed at various seasons in Sunderban area **(NASA, 2017)**

6.2.3 Modeling of biomass gasifier

The load fed by the biomass power, $P_{bio}(k)$ at kth instant is given by Eqn (6.3)

$$P_{bio}(k) = L(k) - P_{solar}(k) - P_{wind}(k) \tag{6.3}$$

Where $L(k), P_{solar}(k)$ and $P_{wind}(k)$ are total load, load fed by the solar power and load fed by the wind power respectively.

The power output of the biomass gasifier, P_{bio} is given by Eqn 6.4 (Chauhan and Saini, 2016).

$$P_{bio} = \dot{S_h} \times CV_s \times \eta_G \tag{6.4}$$

Where $\dot{S_h}$ is the hourly is feed rate of straw, CV_s is the calorific value of straw and η_G is the electrical conversion efficiency of the biomass gasifier-gas engine combination.

6.2.4 Modeling of anaerobic biogas digester

The heat output of the biogas (consisting mainly methane) due to combustion is given by Eqn 6.5

$$H_{biogas} = Y \times D_a \times CV_{biogas} \times \eta_c \tag{6.5}$$

Where Y is the yield of biogas per kg of dung, D_a is the amount of dung fed to biogas digester, CV_{biogas} is the calorific value of biogas and η_c is the efficiency of the combustion.

6.2.5 Ethanol production and separation unit

Ethanol is produced by the water gas shift reaction. Ethanol is produced in the ethanol synthesis unit by the direct hydrogenation of CO **(Jana and De, 2015 a)**as shown in Eqn 6.6.Carbon monoxide and hydrogen reacts under certain temperature and pressure condition to produce ethanol and water along with heat

$$2CO + 4H_2 = C_2H_5OH + H_2O + \Delta H \tag{6.6}$$

6.2.5.1 Catalyst requirement for ethanol production

The annual catalyst requirementC_{ethy} for ethanol production is given by Eqn 6.7 (Ray et al, 2017)**.**

$$C_{ethy} = \frac{Eth_y}{Eth_{kg}} \tag{6.7}$$

6.2.6.Waste heat recovery system

The waste heat generated by the gas engine W_H is given by Eqn 6.8**.**

$$W_H = E_{ge} \times F_g \times F_{sp} \times (t_g - 180) \tag{6.8}$$

Where E_{ge} is the electricity output of the gas engine, F_g is the amount of flue gas generated per kWh of electricity, F_{sp} is the specific heat of the flue gas and t_g is the temperature at the exit of the turbo generator in degree centigrade and it is taken as the limit that the exit gas temperature can not be less than 180°C.(BEE, 2015)

6.2.6.1 Total heat generated

The total heat generated, H_{total}, will be used in the TVC unit as well as to run the vapor absorption chiller. The total heat generated is given by Eqn 6.9**.**

$$H_{total} = W_H + H_{biogas} \tag{6.9}$$

A part of the total heat is used to run the vapor absorption cooling system and the rest is used in the TVC unit to generate potable water.

6.2.7. Vapor absorption chiller

The minimum amount of heat required, $\mathrm{H}_{\boldsymbol{vam}}$, to run the vapour absorption chiller is given by Eqn 6.10**.**

$$\mathrm{H}_{\boldsymbol{vam}} = \frac{\mathrm{VAM}_{\boldsymbol{cap}}}{\mathrm{VAM}_{\boldsymbol{cop}}} \tag{6.10}$$

Where VAMcap is the cooling capacity of the vapour absorption chiller and VAMcop is the coefficient of performance (COP) of the vapour absorption chiller.

6.2.8. Thermal vapor compression (TVC) unit

Brackish water is fed to the TVC unit to get potable water which is another utility output of this polygeneration process as shown in Eqn 6.11.

$$W_{potable} = \frac{W_{brackish}}{H_{waterkg}} \tag{6.11}$$

Where Wpotableis the amount of potable water yield, $\mathrm{W}_{\mathrm{brackish}}$ is the amount of brackish water fed to TVC unit and $\mathrm{H}_{\mathrm{waterkg}}$ is the amount of thermal energy required to yield 1 kg of potable water from brackish water.

6.2.9. Load curve formulation

The variation of electricity consumption pattern over a full day is the corresponding load curve. For the locality considered, the industrial electricity load is practically absent. The total load T_{L} is given by Eqn 6.12. In the rainy season the agricultural electricity load is almost absent because in these times no water is needed for pumping water as rainwater in this region is sufficient for this purpose.

$$T_L = T_D + T_A + T_S \tag{6.12}$$

Where T_D is the domestic load, T_A is the agricultural load and T_S is the street light load.

The variation of the load curve in various seasons is shown in **Fig 6.4.**

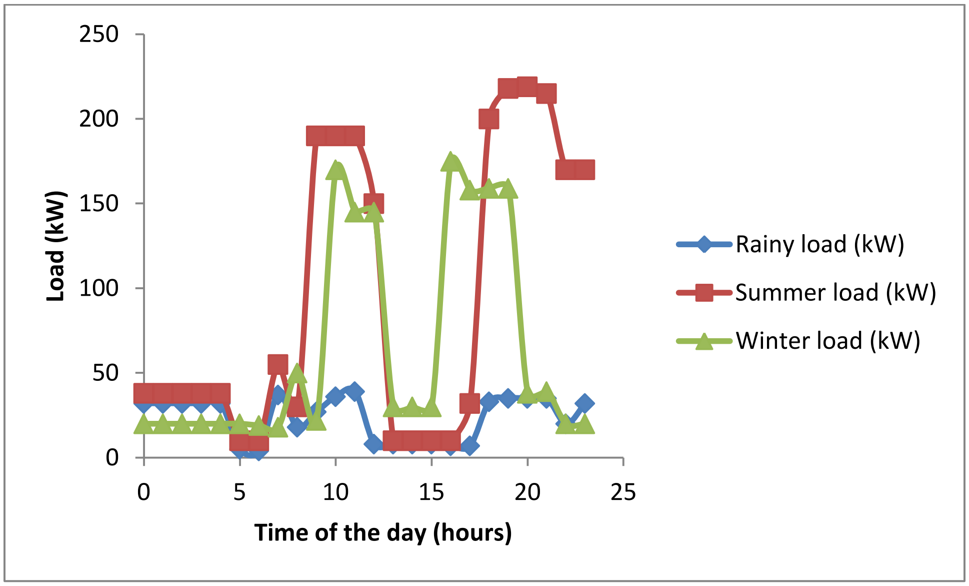


Fig 6.4: Load curve at various seasons

The maximum load is experienced during the evening of the summer season. The gadgets used commonly by the villagers are shown in **Table 6.1.**Theload curve is formulated assuming 1000 households. with a population of 3000.

Table 6.1: Common gadgets used by the villagers

Gadgets used	Power consumption (Watt)	Number per household	Time of operation
Tubelight	55	2	6 p.m.-9p.m.
Incandescent bulb	60	1	6 p.m.-9 p.m.
Mobile charger	5	2	Anytime throughout the day
Fan	60	2	Throughout the day and totally non operational in winter
Street light (Tubelight)	55	100 in total village	6 p.m-9 p.m
Agricultural pumpset	400	50 in total village	3 p.m to 5p.m and totally non operational in rainy season

6.2.10. Economic modeling

The basic input values for the economic modeling is shown in **Table 6. 2**.

Table 6.2: Input data for economic calculation

Serial No	Parameter	Value
1	Solar module price	0.883 USD/W_p
2	Scale factor for biomass gasification systems	0.6 (Jana and De, 2015a)
3	Scale factor for biogas digester systems	0.7 (Jana and De, 2015a)
4	Scale factor for ethanol synthesis	0.7 (Jana and De, 2015a)
5	Scale factor for ethanol separation	0.8 (Jana and De, 2015a)
6	Dung cost	1.8 INR /kg
7	Straw cost	7.80 INR/kg
8	Sell price of ethanol	40 INR/litre
9	Cost of wind turbine	87000 INR/kW(Jana and De, 2015b)
11	Cost of TVC unit	9360 INR/m^3(IRENA, 2017)
12	Operating hours of the plant	8760 hours
13	Cost of waste heat recovery system	999960 INR
14	Cost of waste heat recovery vapour absorption system	53333 USD
15	Cost of a 10kW_e biomass gasifier	666.6USD
16	Cost of potable water	0.25 USD/litre
17	Cost of cooling utility	20 USD/MMBtu
18	Bank discount rate	10%
19	Cost of battery	100 USD/kWh

6.2.10.1 Cost of biomass systems

The annualized cost of the solar module and the wind turbine is obtained by multiplying the installed capacity with the cost per kW.

The cost of the biomass gasifier is given by **Eqn (6.13)(Jana and De, 2015b)**.

$$C_{eqb} = CRF_G \times C_{eqa} \times \left(\frac{C_b}{C_a}\right)^s \tag{6.13}$$

Where C_{eqb} is the cost of biomass gasifier of capacity b, C_{eqa} is the cost of biomass gasifier of capacity a and s is the scale factor. The scale factors are different for the wet and dry biomass based systems as shown in **Table 6.3.**

Table 6.3: Constraints of optimization

Serial No	Parameter	Magnitude
1	Reliability of power supply	100%
2	Yield of biogas per kg of dung	0.3 m^3(Khan et al, 2014)
3	Methane content of the dung	65% (Khan et al, 2014)
4	Calorific value of biogas	2.9MJ/m^3
5	Yearly availability of straw	4.8 kt/year (Biomass Resource Atlas, 2017)
6	Minimum amount of biomass power from gas engine	1.5kW
7	Minimum yield of potable water	9000 litres/day (PHED, 2017)
8	Derating factor of PV module per year	2%
9	Calorific value of straw	14 MJ/kg
10	Heat required for yielding potable water	227 MJ/m^3 (Al-Karaghouli, 2017)
11	COP of vapor absorption chiller	0.7
12	Maximum power extraction coefficient of wind turbine	0.4

6.2.10.2 Cost of solar PV

The annualized cost of solar PV, C_{pv} is given by Eqn6. 14**.**

$$C_{pv} = CRF_{pv} \times C_{pvperkw} \times PV_{installed} \tag{6.14}$$

Where $C_{pvperkw}$ is the cost of PV module per kW and $PV_{installed}$ is the total installed capacity of the PV module.

6.2.10.3 Cost of wind turbine

The annualized cost of wind turbine C_{wind} is given by Eqn 6.15**.**

$$C_{wind} = CRF_{w} \times C_{windperkw} \times Wind_{installed} \tag{6.15}$$

where$C_{windperkw}$ is the cost of installation of wind turbine per kW and $Wind_{installed}$ is the total installed capacity of the wind turbine.

6.2.10.4 Cost of ethanol synthesis unit

The cost of ethanol synthesis unit C_{etsy} is given by Eqn 6 16

$$C_{etsy} = 7.4 \times 10^6 \times \left(\frac{E_{syn}}{31176000}\right)^{sy} \tag{6.16}$$

Where $E_{syn}$the total amount of ethanol synthesized and sy is is the scale factor of the cost of ethanol synthesis unit.

6.2.10.4.1 Cost of ethanol separation unit

The cost of ethanol synthesis unit C_{etss}isgiven by Eqn 6.17

$$C_{etss} = 64.4 \times 10^6 \times \left(\frac{E_{syn}}{31176000}\right)^{se} \tag{6.17}$$

Where se is the scale factor for ethanol separation.

6.2.10.4.1.1 Total cost of ethanol production units

The annualized total cost of the ethanol producing units C_{eth} is given by Eqn 6.18.

$$C_{eth} = CRF_{eth}(C_{etsy} + C_{etss}) \tag{6.18}$$

6.2.10.5 Total yearly cost of straw

The total cost of straw C_{straw}, is given by Eqn 6.19.

$$C_{straw} = \dot{S_h} \times C_{strawperkg} \times 8760 \tag{6.19}$$

where$\dot{S_h}$ is the hourly feed rate of straw and $C_{strawperkg}$ is the cost of 1 kg of straw.

6.2.10.6Total yearly cost of cattle dung

The total cost of cattle dung per year C_D is given by Eqn 6.20

$$C_D = C_{Dperkg} \times D_a \times 365 \tag{6.20}$$

Where $C_{Dperkg}$the cost of 1 kg of cattle is dung and D_a is the quantity of available dung per day.

6.2.10.7 Capital recovery factor (CRF)

The capital recover factor is given by Eqn 6.21(Homer Energy, 2017).

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{6.21}$$

Where i is the bank discount rate and n is the life of individual equipments in years.

6.2.10.8 Annualized Investment (AI)

The annualized investment AI is given by Eqn 6.22

$$AI = \left(C_{eqb} + C_{pv} + C_{wind} + C_{eth} + C_B + C_{vam} + C_{WHRS} + C_{TVC}\right) + C_D + C_{straw} \quad (6.22)$$

Where C_{eqb} is the annualized cost of biomass gasifier, C_{pv} is the annualized cost of PV module, $C_{wind}$is the annualized cost of wind turbine, C_{eth} is the annualized total cost of ethanol production unit, is the cost of battery,C_{vam} is the annualized cost of vapor absorption chiller, C_{WHRS} is the annualized cost of waste heat recovery system, C_D is the annual cost of dung and C_{straw} is the annual cost of straw and C_B is the annualized cost of batteries and C_{TVC} is the .annualized cost of TVC unit

6.2.10.9 Annualized Revenue (AR)

The annualized revenue, AR, is given by Eqn 6.23.

$$AR = Eth_R + C_R + W_R \quad (6.23)$$

Where Eth_R, C_R, W_R are the annual revenues earned by selling ethanol, cooling utility and potable water respectively.

6.2.10.10 Levelized cost of electricity (LCOE)

LCOE represents the overall economic performance of the plant considering all the factors.

The LCOE is given by Eqn 6.24

$$LCOE = \frac{AI - AR}{E_y} \quad (6.24)$$

Where AI is the annualized investment, AR is the annualized revenue collected and E_y is the total units of electricity generated per year. In case of the renewable energy system, the maintenance cost is very low compared to the initial cost. So, it is neglected for this study.

6.2.11. Reliability analysis

In this study the Loss of Power Supply Probability (LPSP) method is used for reliability analysis of the system. This method is used because this method takes into account both the amount of power failure and the hours of power failure simultaneously. The variation of LCOE with the reliability of power supply is studied in this paper. In Indian context, the LCOE is a very important parameter to assess the social acceptance of the energy system. The LPSP is given by **Eqn 6.25 (Sinha and Chandel, 2015).**

$$LPSP = \frac{\sum_{k=1}^{k=n} E_D}{\sum_{k=1}^{k-n} E_L} \times 100 \tag{6.25}$$

Where E_D is the total electrical energy deficit per year and E_L is the total electrical energy required per year.

6.2.12. Optimization scheme

In this paper optimized size of solar module and biomass gasifier are determined using Quantum Inspired Cuckoo Search Algorithm (QICSA). This advancement of CSA has already been proved as efficient for solving some hard hitting optimization problems like bin pacing problem, knapsack problem and few more. Performance of QICSA is also tested for several benchmark functions. In the present paper optimization is carried out as minimization of LCOE, i.e. for optimization an objective function defined in Eqn 6.24 is used to minimize the LCOE. Constraints of the system are also incorporated within the objective function, so that it can be handled while minimizing the objective function value. Initial population for the algorithm is generated randomly within the lower and upper bound. When the load is low, the saved syngas, generated by the biomass gasifier (i.e. the syngas which is not used for power generation) is diverted towards the production of ethanol. In this polygeneration system battery storage is also used. This is because the availability of wind resource is erratic in nature. So if at some instances the availability of wind resource is very high then the battery may be used to store power for future use. Optimized size of different components of the proposed system corresponding to the optimized size of solar module and biomass gasifier are shown in **Table 6.4**.

Table 6.4: Optimized size of the components available from objective function

Serial No	Name of component	Capacity
1	Solar PV module	6 kW
2	Wind turbine	10 kW
3	Biomass gasifier	219 kW_e
4	Ethanol producing unit	2664 litres/year
5	LCOE with free drinking water	12INR/kWh
6	LCOE with drinking water @ 15 INR/litre	6 INR/kWh
7	Size of battery	60 kWh

QICSA can be proved to be better than standard CSA, as it reaches at global optima in fewer iterations rather than CSA. Moreover, comparing the optimized solutions generated using QICSA and CSA; it can be observed that using QICSA value of LCOE is minimized more keeping the number of iterations constant.

6.2.12.1 Brief overview of Quantum Inspired Algorithms

Quantum-inspired algorithms belong to a set of new class of optimization algorithms implemented using the theory of Quantum Computing. Key objective of quantum computing is to discover quantum algorithms which are much more efficient and quicker than the classical algorithms. The basic component of quantum computing is “qubit”. It is a unit vector defined over two-dimensional Hilbert space, where a particular basic state can be indicated by $|0\rangle$ and $|1\rangle$.

Based on the fundamental concept of the superposition principle, if a quantum system can be represented by any one of the two basic states, then it can also be represented as a linear combination of these two states, such as $\alpha_0|0\rangle + \alpha_1|1\rangle$, where the coefficients α_0 and α_1 are the "amplitudes" of the states $|0\rangle$ and $|1\rangle$ respectively. These coefficients give the probabilistic measure of the occurrence of state $|0\rangle$ and state $|1\rangle$ respectively. The superposition of $\alpha_0|0\rangle + \alpha_1|1\rangle$ is the basic, or the smallest, unit of encoded information in quantum computers or quantum systems. The qubit representation is given by **Eqn 6.26**:

$$|\varphi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle \qquad (6.26)$$

According to the superposition principle, α_0 and α_1 are arbitrary complex numbers and the squares of their norms add up to 1, as indicated in **Eqn 6.27**.

$$|\alpha_0|^2 + |\alpha_1|^2 = 1 \qquad (6.27)$$

α_0 and α_1 are the probabilistic amplitude of the qubit that may exist in one of the two states (state "0" or state "1") and ensure that the normalization condition is met.

6.2.12.2. Brief overview of Cuckoo Search Algorithm (CSA)

CSA is based on the brood parasitism of some cuckoo species. Brood parasitism is the special behavior of some species to lay their eggs in communal nests **(Yang and Deb, 2010)**. Sometimes they destroy host birds' eggs to enhance the probability of hatching their own eggs. Thus they involve the host birds into rearing their progenies and dedicate more time in the process to lay more eggs instead of devoting time and energy in parental care. Host birds are either other individuals of same species or some other species. If host birds become successful in identifying any egg as not their own, they either simply destroy the egg or moves away from the nest to build a new nest elsewhere. Cuckoo Search involves predefined parameter bounds that state the domain to choose the initial population. Cuckoo Search uses a balanced composition of a local random walk and global explorative random walks, controlled by a switching parameter p_a. The local random walk can be defined by the **Eqn 6.28.**

$$x_i^{t+1} = x_i^t + \alpha s \otimes H(p_a - \epsilon) \otimes (x_j^t - x_k^t) \quad (6.28)$$

where, x_j^t and x_k^t are two different candidate solutions selected randomly by random permutation, $H(u)$ is a Heaviside function, ϵ is a random number drawn from a uniform distribution and s is the step size. Here, $\otimes$ stands for the entry-wise of two vectors. Global random walk is carried out by a superior kind of random walk namely Lévy Flights. Lévy Flights are capable of maximizing the probability of resource searches in uncertain surroundings. In Optical science, Lévy flight can be defined as a term used to designate the motion of light. Survey says, by performing Levy flights more vast area can be covered than normal random search. Performing Levy Flight is also additionally informative than the traditional search methods. Some shark species follow random Brownian motion while searching food; however, if they failed to get food items, they start following Lévy flight behaviour, mixing short random movements with long trajectories. Global random walk using Lévy flight is defined by the following **Equations 6.29, 6.30, 6.31**:

$$x_i^{t+1} = x_t^i \alpha L(s, \lambda); \quad (6.29)$$

$L(s, \lambda) = \frac{\lambda \Gamma(\lambda) \sin(\pi\lambda/2)}{\pi} \frac{1}{s^{1+\lambda}}$, $(s \gg s_0 > 0)$; $\alpha > 0$ is the step size scaling factor. (6.30)

x_i^{t+1}andx_i^t are the solutions i at iteration at$t + 1$and t respectively.

Step length (λ) is drawn from a Lévy distribution defined by the following equation having an infinite variance with an infinite mean:

Lévy$\sim u = t^{-\lambda} (1 < \boldsymbol{\lambda} \leq \mathbf{3})$ (6.31)

6.2.12.3. Quantum Inspired Cuckoo Search Algorithm (QICSA)

At the beginning of solving an optimization based problem using QICSA, a set of solutions termed as initial population is generated but within a specific range demarcated by lower and upper bounds. In the next step, quantum representation of all the solutions in the initial population is performed. In QICSA also balanced composition of a local random walk and global explorative random walks is used for generating new solutions with the aim of replacing old worse solutions. Local random walk is performed following the similar way performed in CSA using the **Eqn. 6.28.** In order to perform global random walk using Lévy flights**,** Equn 6.32 and 6.33 are used

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(g_* - x_i^t) + \alpha|c_t - x_i^t| \ln(1/u_i^t) \tag{6.32}$$

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(g_* - x_i^t) - \alpha|c_t - x_i^t| \ln(1/u_i^t) \tag{6.33}$$

$$c^t = \left(\frac{1}{N}\sum_{i=1}^{N} p_{i,1}^t, \frac{1}{N}\sum_{i=1}^{N} p_{i,2}^t, \dots, \frac{1}{N}\sum_{i=1}^{N} p_{i,d}^t\right) \tag{6.34}$$

$$p_i^t = x_i^t + \gamma L(\lambda)\left(g_* - x_i^t\right) \tag{6.35}$$

x_i^{t+1} and x_i^t are the solutions i at iteration $t+1$ and t respectively. g_* stands for global best solution. $\gamma$is scaling factor used to control the step size. $\lambda$is the step length which can be drawn from a Lévy distribution defined using the Eqn 6.31**.**$c_t$states the superposition of the solutions of the current population. $\alpha$is contraction expansion coefficient which can be tuned to control the convergencespeed of the algorithms and u_i^t is a random variable uniformy distributed between [0,1]. Value of α can computed using **Eqn 6.36**:

$$\alpha = (1 - t)/MaxIteration * 0.5 \tag{6.36}$$

The algorithm is detailed in Algorithm 1. The sequential stepwise operation of this algorithm for this problem i.e. finding the optimized sizes of the components of this polygeneration system is given in **Fig 6.5**.

```
Input: Total No. of Iteration ($Max\_iteration$), size of population (m), objective function($l$), lower bound, upper bound, probability $p_a$ for discovering worse quality nests
Output: Global Best Solution.
Begin
Define objective function $l(x), x = (x_1, x_2, \dots., x_d)$
Initialize a population of m nests
Evaluate the fitness of the solutions using $l$
Find the best quality nest and store in $BEST$
Store fitness value of $BEST$ in $gmin$
Define a switch probability p [0, 1] and scaling factor $\gamma$
$t = 1$
while($t < Max\_iteration$)
  Define $c^t$ by Eqn 34
for$i = 1: N$
 Generate a random number $q$
$\alpha = (1 - t)/Max\_iteration * 0.5$
        Draw a (d-dimensional) step vector L which
        Obeys aLévy distribution
if ($q > 0.5$)
         Generate new solution using Eqn. 32
else
         Generate new solution using Eqn. 33
end if
Discover worse nests with probability $p_a$
      Replace worse nests by the new nests
      Generated using the Eqn. 28
end if
     Evaluate the fitness of the solutions using $f$
    Find the current best nest $c_{best}$ and store its
  fitness value in $lmin$
  if ($lmin < gmin$)
       Update $BEST$ and $gmin$
    End if
                                                  $t = t + 1$
End while
End
```

Figure 6.5: Generalized steps of QICSA algorithm

The constraints of optimization are shown in **Table 6.3.**

Table 6.3: Constraints of optimization

Serial No	Parameter	Magnitude
1	Reliability of power supply	100%
2	Yield of biogas per kg of dung	0.3 m^3 **(Khan et al, 2014)**
3	Methane content of the dung	65% **(Khan et al, 2014)**
4	Calorific value of biogas	2.9MJ/m^3
5	Yearly availability of straw	4.8 kt/year **(Biomass Resource Atlas, 2017)**
6	Minimum amount of biomass power from gas engine	1.5kW
7	Minimum yield of potable water	9000 litres/day **(PHED, 2017)**
8	Derating factor of PV module per year	2%
9	Calorific value of straw	14 MJ/kg
10	Heat required for yielding potable water	227 MJ/m^3 **(Al-Karaghouli, 2017)**
11	COP of vapor absorption chiller	0.7

6.3 Results and discussion

In this paper, the size of the individual components of the polygeneration system is determined using QICSA. The size of the biomass gasifier corresponds to the maximum when the maximum load occurs i.e. during night when solar power is absent and wind power is also not available significantly. When the load is low, the saved syngas, generated by the biomass gasifier (i.e. the syngas which is not used for power generation) is diverted towards the production of ethanolIn this polygeneration system a battery storage is also used. This is because the availability of wind resource is erratic in nature. So if at some instances the availability of wind resource is very high then the battery may be used to store power for future use. The optimized sizes of the components of the polygeneration system are shown in **Table 6.4.**

Table 6.4: Optimized size of the components

Serial No	Name of component	Capacity
1	Solar PV module	6 kW
2	Wind turbine	10 kW
3	Biomass gasifier	219 kW_e
4	Ethanol producing unit	2664 litres/year
5	LCOE with free drinking water	7.21 INR
6	LCOE with drinking water @ Rs 15/litre	6.49 INR

The QICSA proves to be a better algorithm than cuckoo search algorithm as shown in **Fig 6.6**

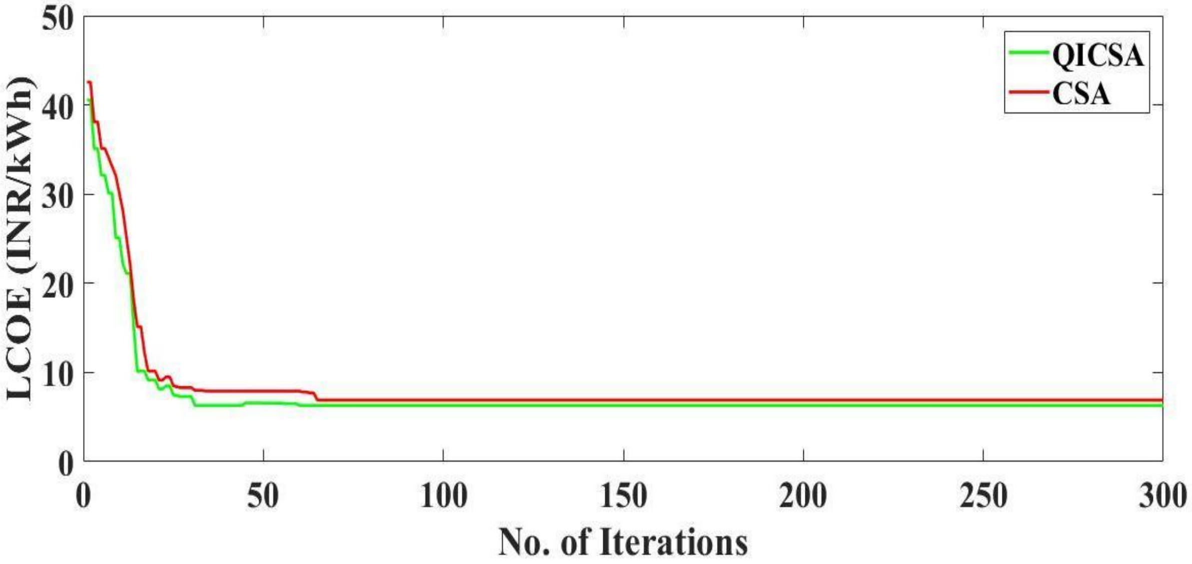


Fig 6.6: LCOE with the application of CSA and QICSA

This is because in QICSA the search is performed by the combinations of local and global random walks. The use of quibit in the quantum inspired algorithms is better in terms of search space i.e. more individual samples in the search space is addressed. Thus the minimum LCOE is achieved in less number of iterations than CSA.

6.3.1. Sensitivity analysis

In the present study, economic modeling is carried out. The input variables are the sizes of the components and the costs associated with them. The economic model is the main input to the optimization algorithm. The prices of the components are varying in nature due to the technical and other socio-economic factors. Hence the effect of uncertainties of the input to the output model is carried out in sensitivity analysis. The sensitivity analysis is useful to the policy makers to decide the suitability of the system in a varying price environment. The sensitivity analysis of this polygeneration system is shown in **Figs 6.7(a-g).**

In **Figure 6.7(a)**, the effect of hybridization is studied. Renewable resources are intermittent in nature. However, multiple renewable resources may be available at the same place. When one resource is not available, another may be available with different capacity. Hybridization may be a possible option for the efficient use of the renewable resources. Results of the study shows that hybridization of more types of renewable resources results a lowering of the LCOE. The least LCOE is obtained when almost all the possible available resources found in this area of study is hybridized in the same system to deliver electricity.

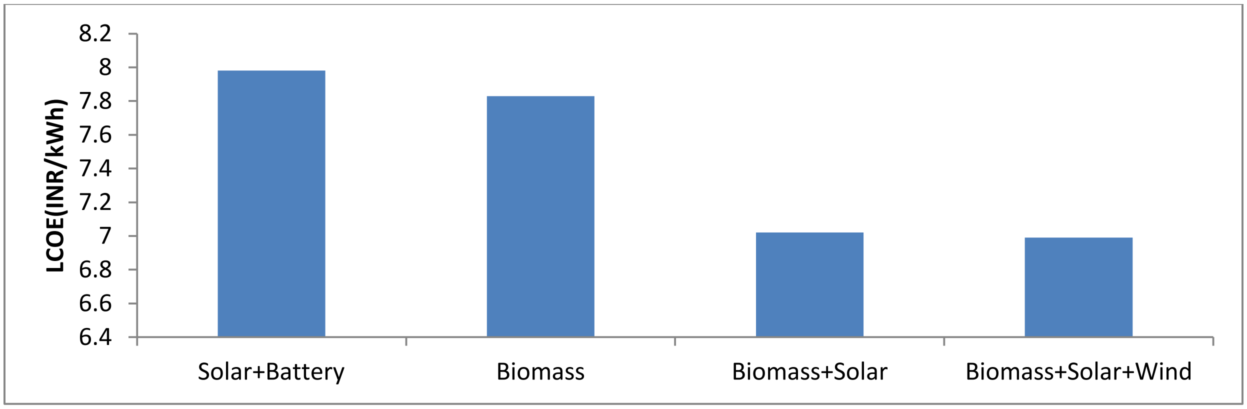


Fig 6.7 (a): Variation of LCOE with Different hybridization combinations with only electricity as output

Figure 6.7 (b) shows the variation of LCOE with the addition of more output utilities. When multiple utilities are obtained from the same system through efficient process integration, then the LCOE decreases. This is because the efficient process integration increases the overall efficiency of the system. The addition of economic value of these utilities decreases the LCOE which is a better socially acceptable solution. The LCOE is the least when the polygeneration system delivers electricity, ethanol and chill as the utility outputs. The LCOE increases by about 10% when potable water is added as one output. This is because of the addition of the TVC unit which is capital intensive. But drinking water is an essential need for the people in this locality to survive as these islands are surrounded by saline water creeks. So potable water should be added as an utility output of this polygeneration system.

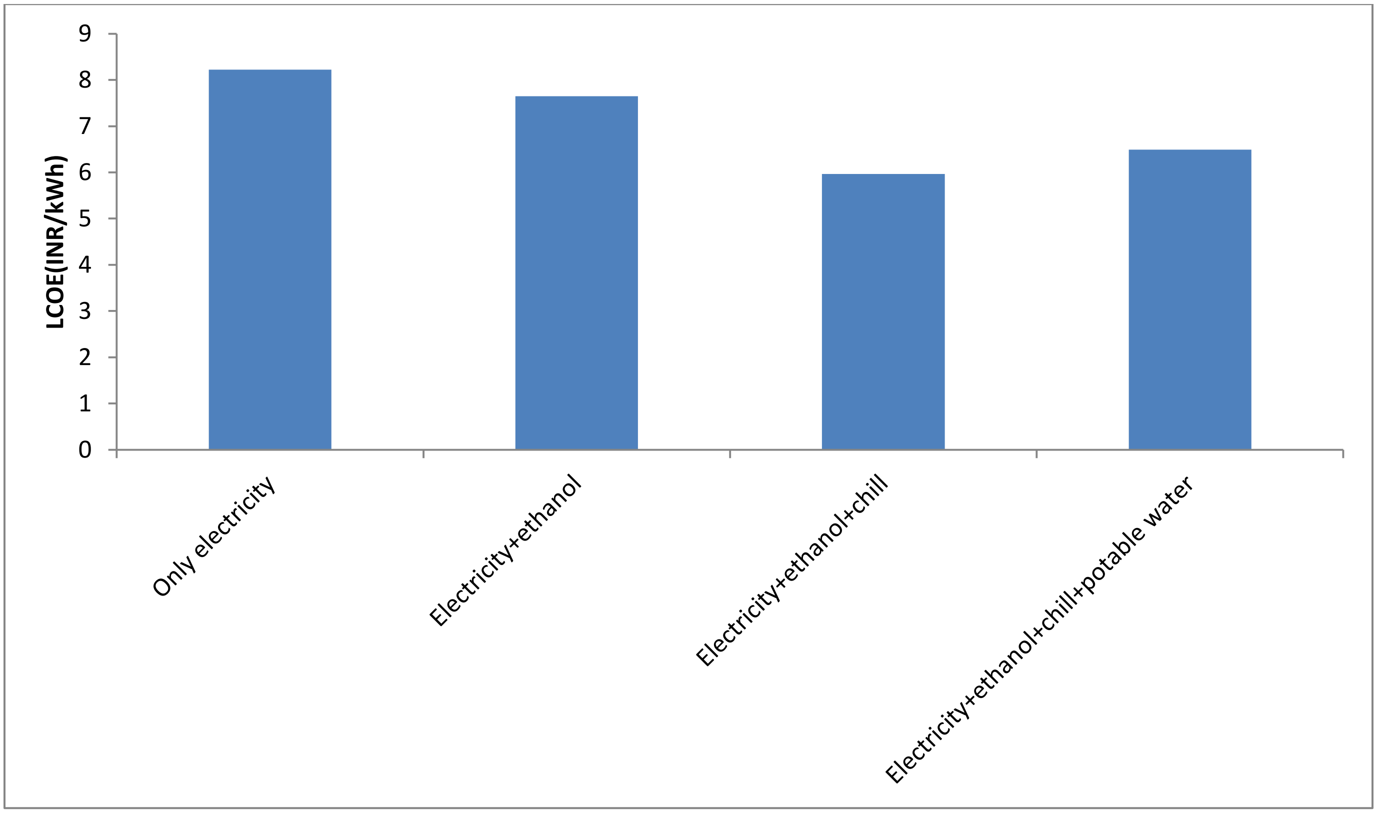


Fig 6.7(b): Variation of LCOE with the addition of utilities

Figure 6.7(c) shows the variation of the LCOE with the variation of the price of the solar module. Due to technological advancements and various policies adopted by the government, the prices of the solar module are decreasing. In this polygeneration system solar module generates electricity. Moreover, in the power mix if the percentage of solar power increases then the ethanol synthesis from the syngas also increases which is also a source of revenue. If the solar module price increases above 69.60INR/kW then the LCOE abruptly increases by about 15%. This is because in this case the optimum size of the solar module changes from 6kW to 3kW. This results in the lowering of ethanol synthesis as more syngas is utilized for power.

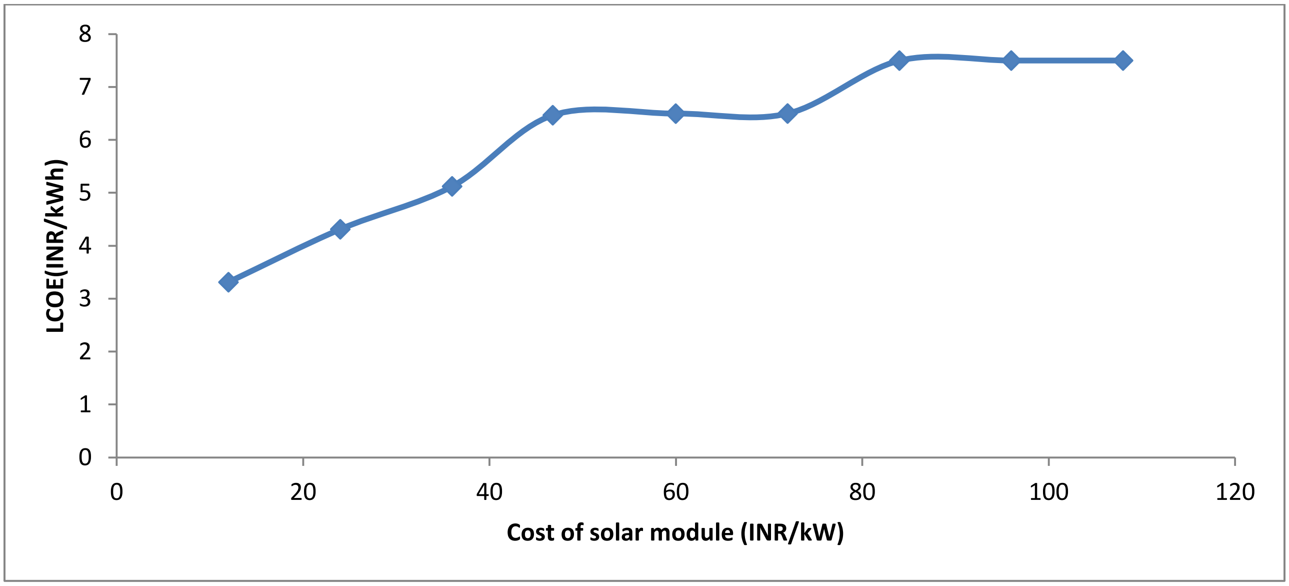


Fig 6.7 (c): Variation of LCOE with Price of solar module

Figure6.7 (d) shows the variation of the LCOE with the price of ethanol. In this polygeneration, ethanol is also a revenue generator. Low cost is one of the key factors to make a system socially acceptable especially in Indian context. In this study, the excess syngas after meeting the electricity demand is used for ethanol synthesis. Keeping into consideration the price sensitivity of the Indian electricity market, the effect of the price of ethanol on LCOE is studied for two different reliability of power supply i.e. 100% reliability of power supply and 80% reliability of power supply. For both cases, it is observed that the LCOE decreases abruptly by about 20% if the cost of ethanol is increased to 52.80 INR/litre. This is because in this case the solar module size increases from 6kW to 10kW, but still the LCOE is lowered as at that time more amount of syngas is converted to ethanol and it is sold. Increased per unit price of ethanol leads to more revenue generation and thus reduces the LCOE.

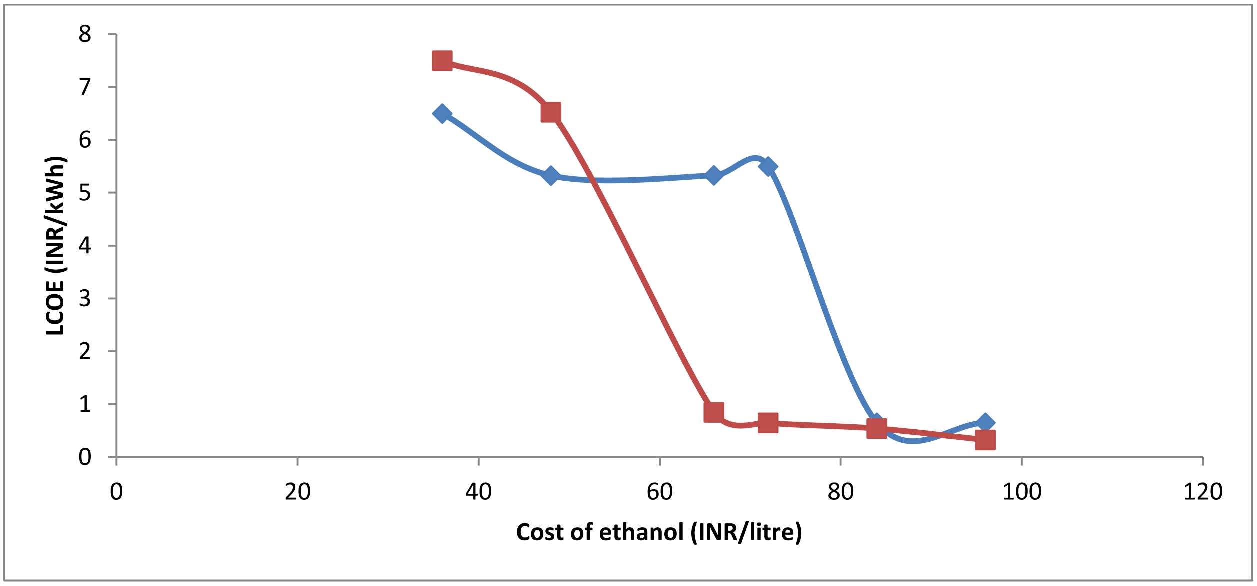


Fig 6.7 (d): Variation of LCOE with Cost of ethanol

Figure6.7 (e) shows the variation of the LCOE with the cost of straw. In this polygeneration system only the "excess" straw i.e. the straw which remains after feeding the cattle is used. Due to change in socio- economic factors, the cost of straw may vary. The effect of the cost of straw on LCOE is studied as straw is the principal renewable fuel for the generation of electricity for this study. Moreover, straw is also used to generate syngas that is used for the synthesis of ethanol. In this study the LCOE remains constant if the cost of straw increases even beyond 10 INR/kg. This is because unit cost of straw is not so high. Only the 'excess' straw is used.

Moreover if the unit cost of straw increases beyond 19 INR/kg, then the percentage of solar power in the grid increases thus keeping the LCOE constant .It is used both for the purpose of generating electricity and the production of ethanol. Both of these utilities generate revenue thereby lowering LCOE more.

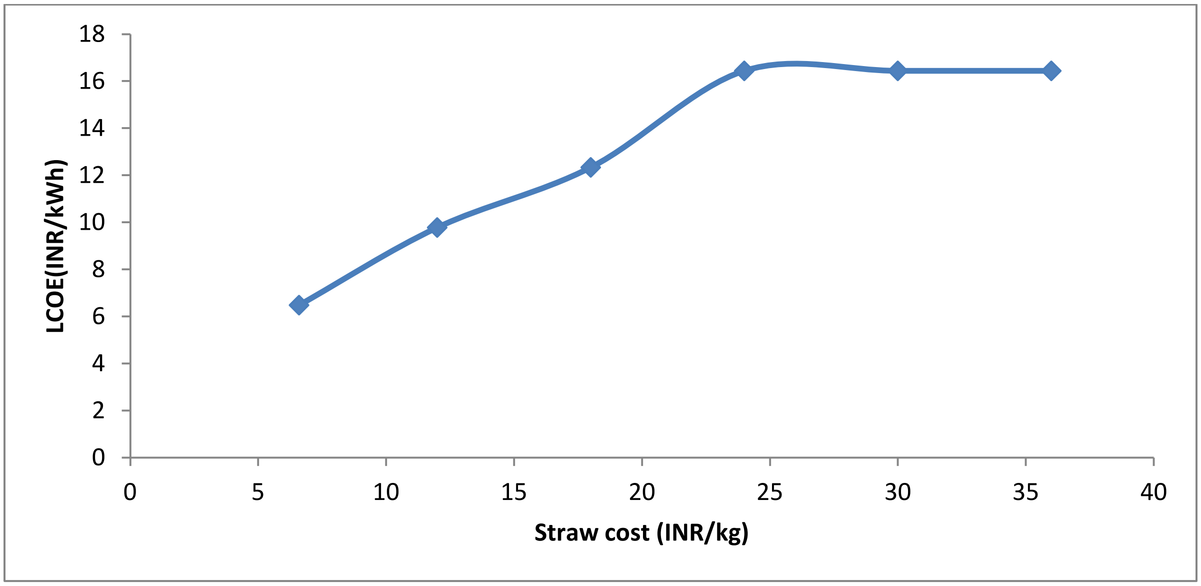


Fig 6.7 (e): Variation of LCOE with Cost of straw

Figure 6.7 (f) shows the variation of LCOE with the reliability of power supply. The reliability of power supply is calculated using the LPSP method as shown in **Eqn6. 25**. The LPSP method is used as it takes into account both the magnitude of power shortage and the hours of power failure. It is observed that that with the increase of reliability of power supply above 50% the LCOE decreases which is a better socially acceptable solution.

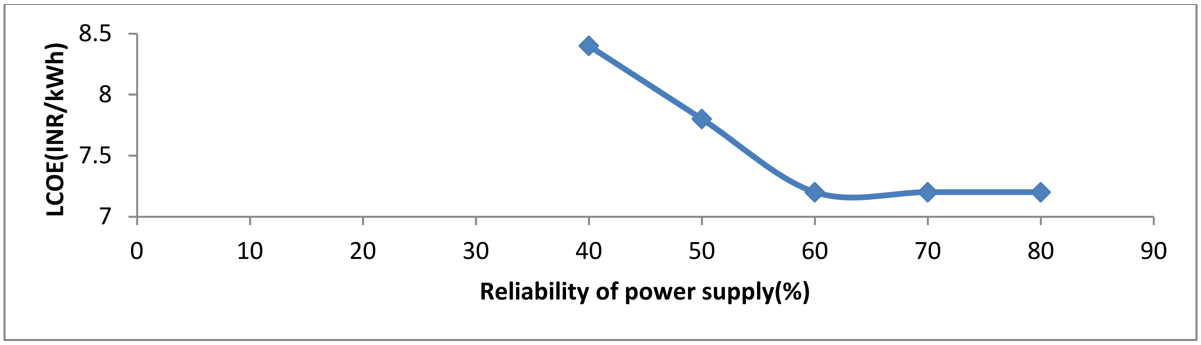


Fig 6.7 (f): Variation of LCOE with Reliability of power supply

Figure 6.7 (g) shows the variation of LCOE with the multiples of the load curve i.e. the load of all the instances is multiplied by a fixed factor. Population growth in India is generally high. With increasing population, the electricity consumption increases but the pattern remains almost same. So in this study, the loads in each instant of the load curve (**as shown in Fig 6.4**) is multiplied by the same factor like 2,3,4 etc and its effect on LCOE is studied.It has been seen that if the load increases by six times or above than the present load then LCOE decreases by about 25%. This is because here the major electricity generator is biomass gasifier. Another utility output is potable water. This is generated by the heat from the combustion of the biogas produced from the biogas digester. The prices of both of these components do not decrease linearly with the output capacity. Hence if the load increases, the LCOE decreases.

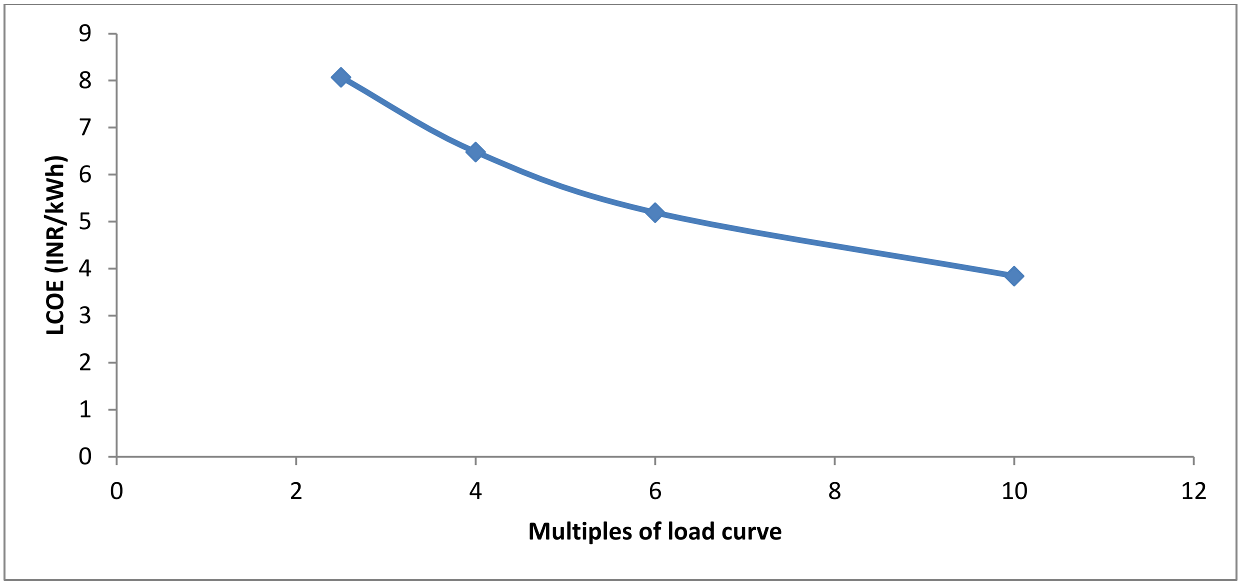


Fig 6.7 (g): Variation of LCOE with multiples of load curve

6.4 Conclusion

For energy sustainability at specific locations, small scale distributed generation using local renewable resources may be a better solution than large scale fossil fuel based power plants. Also to accommodate intermittency and available limited renewable resources, hybridization is a suitable option. Specifically distributed generation may be suitable for remote locations where grid power may not be feasible either technologically or economically. Even several utility outputs may be combined efficiently in a single integrated system with improved performance in a polygeneration. A polygeneration with four utility outputs including electricity has been analyzed with real data of several local renewable resources for a remote place of India. The LCOE is estimated as 0.1081/kWh which is competitive with grid power. This system is proposed for remote Sunderban areas of India where grid power is not feasible. Optimum combination and capacities of different devices using renewable resources to meet local energy and other utility demands for a minimum LCOE is explored using QICSA. Results of the study show that the LCOE decreases when all the available renewable resources at a particular place are utilized i.e. hybridized. It is also observed that the LCOE has decreased by about 18% with the hybridization of more renewable resources than generating electricity with only solar photovoltaic modules and battery for storage. It also decreases with the increase in the number of utility outputs. It is a socially and economically better solution. LCOE also decreases with the increase of instantaneous load and increased reliability of power supply above 50% which is another better social solution.

7. Conclusion and Future Scopes

Most of Indian population lives in villages. Many of the Indian villages are located in very remote and inaccessible terrain and inhabited by poor people. It is almost impossible to connect these villages to the national grid due to terrain conditions. Moreover, costly grid power may not be affordable to the villagers. So, the inhabitants of these villages are generally deprived of many basic energy services like access to electricity, drinking water, transportation fuel etc. The Government of India has taken many programmes for rapid rural electrification. But apart from the above problems the fossil fuel based energy systems also have the serious limitation due to GHG emission. So, distributed small scale energy systems may be a solution for these villages. The distributed renewable energy systems have less capital investment than the centralised generating stations. Moreover, as the basic amenities are lacking in these villages, so an efficiently integrated composite system delivering basic utilities may be a possible source of local development and may emerge as future sustainable solution to all these villages.

The renewable energy systems have some limitations also. The main difficulties are intermittency and low capacity. Unlike fossil fuels, the renewable resources cannot be made available as and when required i.e. following the demand according to the load curve. For this reason, storage becomes inevitable for renewable based energy systems. The most conventional form of storage of electricity is using a battery. But it has serious limitations with respect to capital cost, low life and environmental impact regarding its disposal. However, load matching for such renewable distributed energy system may be possible by hybridization of more renewable resources available in that particular area. Even better distributed option is polygeneration i.e. integration of other energy utilities along with electricity.

As polygeneration is a multi-input and multi-output system, so otpimization of such systems for proper capacity determination is an important issue. In this thesis, the linear programming method, metaheuristic algorithm and quantum inspired metaheuristic algorithms are used for such optimization. Both single objective and multi-objective optimization are carried out with real time data and relevant technical and socio-economic constraints. The comparative analysis shows the superiority of Cuckoo Search Algorithm over the other algorithms. All the results show that addition of more utilities into the integrated energy system i.e. polygeneration lowers the Levelized Cost of Electricity. The study is carried out in villages of Sunderban deltaic region as well as for a village of hilly Uttarakhand in India. Both these studies show that the Levelized Cost of Electricity in polygeneration systems is competitive with grid power. The cost lies between 6 INR to 10 INR/kWh. The increase in the reliability of power supply lowers the Levelized Cost of Electricity which is an even better socially acceptable solution also.

In this study, the optimization of polygeneration systems are made for decentralized generations in different parts of India. The sensitivity analysis is also done for different parts of India. In India, there are places with different climatic and terrain conditions. So, locally available renewable energy resources are also different. So, the study has been made for Sunderban area as well as a hilly terrain of Uttarakhand, India. The objective functions are selected based on technical as well as socio-economic and environmental factors. Both the single objective and the multi objective optimization are carried out. A comparative study on the performance of the various algorithms are also made in the study.

7.1. Future Scopes

Based on reported work in this thesis, following future scope of research also exists:

- Model development and analysis of decentralized polygeneration with intermittent supply of local renewable resources supported by available grid power to match variable load.
- Economic analysis with ‘time value’ of money may be carried out for more realistic conclusions.
- More detail assessment of impact on environment through life cycle analysis (LCA) may be carried out to assess environmental impact for such systems.
- Specific optimization tools like linear, metaheuristic and quantum inspired metaheuristic are used for optimization in this work. A more generalized tool for optimized solution of input-output and capacity determination of polygeneration for a specific locality with known availability of renewable resources may be developed.
- Uncertainty analysis for variation of availability of local renewable resources and corresponding impacts from several aspects could be done in more detail.

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