

# **Optimal Power Management of Hybrid Renewable Energy Systems**

*A THESIS*

*submitted by*

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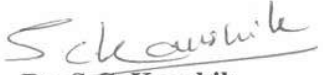
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## THESIS CERTIFICATE

This is to certify that the thesis titled **Optimal Power Management of Hybrid Renewable Energy Systems**, submitted by **Shakti Singh**, to the Thapar University, Patiala for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

  
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## ABSTRACT

Renewable energy systems are proving to be promising and environment friendly sources of electricity generation, particularly, in countries with inadequate fossil fuel resources. The rapid depletion of fossil fuel resources and increase in demand of electricity has renewed interest in micro-grids (MG) consisting of renewable energy sources (RESs) and storage devices. Incorporating RESs and storage devices into MG could play a vital role in enhancing the reliability of the system. In recent years, RESs such as wind, solar photovoltaic (PV) and biomass based systems are drawing more attention to provide electricity to isolated or energy deficient regions. In this research work, various configurations of hybrid energy system which consists of different RESs have been analyzed in terms of reliability and cost. Detailed mathematical model have been developed and a simplified operational strategy have been presented for different configurations. Initially, a detailed survey have been conducted on optimization method used in hybrid energy systems. Based on the survey, a comparative new meta-heuristic algorithm i.e. artificial bee colony (ABC) algorithm has been selected for optimization methods. Further, results obtained by applying ABC algorithm have been compared with other evolutionary technique and software tool. Moreover, a novel voltage droop controller has been proposed for a hybrid system for better power management perspective. Optimal power management of an hybrid energy system is achieved by controlling the charging and discharging rates of individual battery. The efficacy of the proposed controller is verified by considering some critical cases such as the sudden failure of any generating unit. It has been observed that due to sudden failure of any generating unit, proposed controller manages power of the hybrid system by altering charging and discharging rate of the batteries.

**KEYWORDS:** Artificial bee colony algorithm, biomass energy, grid integration, optimization algorithms, micro-gird, solar energy, wind energy.

## LIST OF PUBLICATIONS BASED ON THESIS

1. **(Chapter 1)**

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# Contents

<b>ABSTRACT</b>	<b>iii</b>
<b>LIST OF TABLES</b>	<b>ix</b>
<b>LIST OF FIGURES</b>	<b>xi</b>
<b>ABBREVIATIONS</b>	<b>xii</b>
<b>1 INTRODUCTION AND THESIS OVERVIEW</b>	<b>2</b>
1.1 Introduction . . . . .	2
1.2 Optimization methods applied to hybrid system . . . . .	6
1.3 Optimization software tools . . . . .	7
1.4 Conventional techniques . . . . .	10
1.4.1 Iterative technique . . . . .	10
1.4.2 Linear programming . . . . .	12
1.4.3 Graphical construction method . . . . .	12
1.4.4 Least square method . . . . .	13
1.4.5 Probabilistic approach . . . . .	13
1.4.6 Others techniques . . . . .	13
1.5 Non-conventional optimization techniques . . . . .	14
1.5.1 Genetic algorithm . . . . .	14
1.5.2 Particle swarm optimization . . . . .	15
1.5.3 Biogeography based optimization . . . . .	17
1.5.4 Ant colony optimization . . . . .	17
1.5.5 Artificial bee colony algorithm . . . . .	18
1.5.6 Simulated annealing . . . . .	18
1.5.7 Others techniques . . . . .	18
1.6 Hybrid techniques . . . . .	19

1.7	Multi-objective optimization . . . . .	20
1.8	Power management and control of hybrid systems . . . . .	23
1.9	Scope of the study . . . . .	24
1.9.1	Motivation . . . . .	24
1.9.2	Objectives of the research work . . . . .	25
1.9.3	Contribution . . . . .	26
1.10	Organization of the thesis . . . . .	26
<b>2</b>	<b>HYBRID SOLAR-WIND WITH BATTERY SYSTEM</b>	<b>28</b>
2.1	Introduction . . . . .	28
2.2	Mathematical model of hybrid system . . . . .	30
2.2.1	Solar photovoltaic panel . . . . .	31
2.2.2	Wind power generation . . . . .	32
2.2.3	Battery bank . . . . .	32
2.2.4	Diesel generator . . . . .	34
2.2.5	Power converter . . . . .	35
2.3	Problem formulation and algorithm . . . . .	35
2.3.1	Objective function . . . . .	35
2.3.2	Operational strategy and system constraints . . . . .	37
2.3.3	Operational strategy . . . . .	37
2.3.4	Artificial bee colony algorithm . . . . .	39
2.3.5	Particle swarm optimization . . . . .	42
2.4	Resource data . . . . .	42
2.5	Results and discussion . . . . .	46
2.6	Conclusion . . . . .	49
<b>3</b>	<b>HYBRID SOLAR, WIND AND BIOMASS SYSTEM</b>	<b>50</b>
3.1	Mathematical modeling of proposed hybrid system . . . . .	53
3.1.1	Biomass gasifier . . . . .	54
3.1.2	Battery bank . . . . .	55
3.1.3	Power converter . . . . .	56

3.2	Problem formulation	56
3.2.1	Operational strategy	57
3.2.2	Objective function and constraints	58
3.2.3	Artificial bee colony algorithm	61
3.3	Results and discussions	63
3.3.1	Results analysis	63
3.3.2	Robustness test	69
3.3.3	A special case: failure of one source	71
3.3.4	Effect of the battery's efficiency on LCOE	72
3.4	Conclusion	73
<b>4</b>	<b>GRID INTEGRATED PV-BIOMASS SYSTEM</b>	<b>74</b>
4.1	Introduction	74
4.2	Mathematical modeling of the hybrid system	75
4.2.1	Power inverter	76
4.2.2	Utility grid	77
4.3	Problem formulation	77
4.3.1	Objective function	78
4.3.2	Operational strategy	81
4.3.3	Artificial bee colony algorithm	82
4.4	Resource data and component selection	84
4.5	Results and discussions	85
4.5.1	Standalone system	85
4.5.2	Grid connected system	88
4.6	Conclusion	93
<b>5</b>	<b>HYBRID SYSTEM WITH DISTRIBUTED ENERGY STORAGE</b>	<b>94</b>
5.1	Introduction	94
5.2	Modelling of the system	98
5.2.1	Fuel cells	98
5.2.2	Distributed energy storage systems	99

5.3	Problem formulation . . . . .	99
5.3.1	MG operation . . . . .	100
5.3.2	Voltage control by droop characteristics . . . . .	101
5.3.3	Division of power based on droop characteristics . . . . .	104
5.3.4	Battery control algorithm . . . . .	105
5.4	Results and discussions . . . . .	107
5.4.1	Special case study: solar power breakdown . . . . .	112
5.4.2	Comparison with the existing scheme . . . . .	113
5.5	Conclusion . . . . .	116
<b>6</b>	<b>CONCLUSION AND FUTURE SCOPE</b>	<b>117</b>
6.1	Conclusions from the present work . . . . .	117
6.2	Futuristic aspects . . . . .	119

## List of Tables

1.1	Grid-interactive renewable power in India (Capacities in <i>MW</i> ) . . . . .	4
1.2	Off-grid/captive renewable power in India (Capacities in <i>MW</i> ) . . . . .	4
1.3	Publication in literature using software tool HOMER . . . . .	11
1.4	Advantages and disadvantages of the optimization techniques . . . . .	22
2.1	Technical and economical data of the components used in proposed hybrid system	45
2.2	Parameters of the PSO and ABC algorithms . . . . .	46
2.3	Optimal sizing result received from various techniques . . . . .	47
2.4	Optimal sizing result of different configurations obtained by HOMER . . . . .	49
3.1	Estimated electricity demand for community . . . . .	65
3.2	Technical and economical data of the components . . . . .	66
3.3	Parameters of the PSO and ABC algorithms . . . . .	66
3.4	Optimal sizing result received from various techniques . . . . .	67
3.5	Break down of ASC obtained by the ABC algorithm for the proposed system .	67
3.6	Energy analysis by HOMER, PSO and ABC algorithm . . . . .	67
3.7	Statistics of the results obtained by ABC and PSO algorithms . . . . .	71
3.8	Paired student's t-test results for sample mean . . . . .	71
4.1	Component costs used in proposed study . . . . .	85
4.2	Optimal sizing result for stand-alone hybrid PV-biomass energy system . . . . .	87
4.3	Optimal sizing result for grid connected hybrid PV-biomass energy system . . . . .	88
4.4	Electricity production and consumption by HOMER and applied ABC algorithm . . . . .	89
4.5	Cost analysis obtained by the ABC algorithm for case II ( Table 5) . . . . .	89
5.1	Battery specifications . . . . .	99
5.2	Simulation parameters . . . . .	110

## List of Figures

1.1	Indian power sector at a glance in the year 2016 . . . . .	3
1.2	Percentage share of energy sources in Indian power sector in the year 2016 . . . . .	3
1.3	Different components of a hybrid coupled configuration . . . . .	6
1.4	Generalized steps followed in the optimization of hybrid renewable energy systems . . . . .	8
1.5	A broad classification of optimization techniques . . . . .	9
1.6	Percentage sharing of optimization techniques in literature in last 10 years . . . . .	23
2.1	Different components of the proposed system . . . . .	30
2.2	A typical wind turbine characteristic [Masters (2004)] . . . . .	33
2.3	Load demand in winter and summer season . . . . .	43
2.4	(a) Yearly load demand (b) Solar radiation data for one year . . . . .	44
2.5	(a) Average wind speed data (b) Wind speed histogram . . . . .	44
2.6	Convergence characteristic of the ABC and PSO algorithms . . . . .	47
2.7	Power management indicating load demand, wind, solar, battery input/output and battery SOC (on secondary axis) power in case III of Table 2.4 . . . . .	48
2.8	(a) Battery SOC (%) (b) Battery energy flow for one complete year . . . . .	48
3.1	Different components of the proposed system . . . . .	54
3.2	A simplified flow chart of the operating strategy of the proposed system . . . . .	60
3.3	(a) Daily load profile (winter and summer ( $kW$ )) (b) Solar radiation ( $kW/m^2$ ) (c) Wind speed ( $m/s$ ) . . . . .	64
3.4	Comparison of convergence rates for PSO and ABC algorithms . . . . .	68
3.5	Monthly energy analysis for the proposed case study . . . . .	68
3.6	Energy balance and battery SOC for the third week of January . . . . .	70
3.7	Energy balance (on left y axis) and battery SOC (on right y axis) for the last week of June . . . . .	70
3.8	(a) Battery SOC (%) (b) Battery energy flow for one complete year . . . . .	71
3.9	Solar, wind, battery, biomass energy, load demand and battery SOC (on right y axis) for the last week of June . . . . .	72

3.10	Effect of battery's round trip efficiency on LCOE . . . . .	72
4.1	Schematic diagram of the proposed hybrid grid connected PV-biomass energy system . . . . .	76
4.2	Energy produced by the stand-alone hybrid PV-biomass energy system (scenario A). . . . .	87
4.3	Convergence characteristic of the ABC algorithm for the stand-alone system . . . . .	87
4.4	Convergence characteristics of the ABC algorithm for grid connected system (case II and III of Table 4.3) . . . . .	90
4.5	Monthly average electricity production during one year for case II (Table 4.3) . . . . .	90
4.6	Nominal cash flow during the project lifetime for case II (Table 4.3) . . . . .	91
4.7	Power management indicating load demand, biomass, solar, grid sales and purchased powers in the case II (Table 4.3) . . . . .	91
4.8	Effect of grid sale capacity on PV production, biomass power, grid sales and LCOE for case II (Table 4.3) . . . . .	92
5.1	Proposed MG system with RES, DESS and charging station . . . . .	98
5.2	Schematic diagram of the proposed microgrid system . . . . .	102
5.3	(a) Voltage and frequency droop characteristic of a generator (b) Resistive coupled voltage sources . . . . .	103
5.4	Voltage droop controller . . . . .	105
5.5	Flow chart of the batteries power flow control . . . . .	108
5.6	(a) Solar radiation ( $KWh/m^2$ ) and wind speed ( $m/s$ ) (b) Power generation by various RESs at MG (c) Total power generation, load demand and battery power requirement (charging and discharging mode). . . . .	111
5.7	(a) Power available at MG (b) Power distribution at different CSs . . . . .	112
5.8	Charging and discharging rates at different CSs . . . . .	113
5.9	Battery SOC variations at different CSs . . . . .	113
5.10	Total power met using regulation signal and diesel generator . . . . .	114
5.11	The solar power is shut down at 0800 hour . . . . .	114
5.12	Battery SOC variations at different CSs during sudden shutdown of solar power plant . . . . .	115
5.13	Comparison of the proposed scheme with an existing scheme with respect to battery SOC variations (battery type 1). . . . .	115

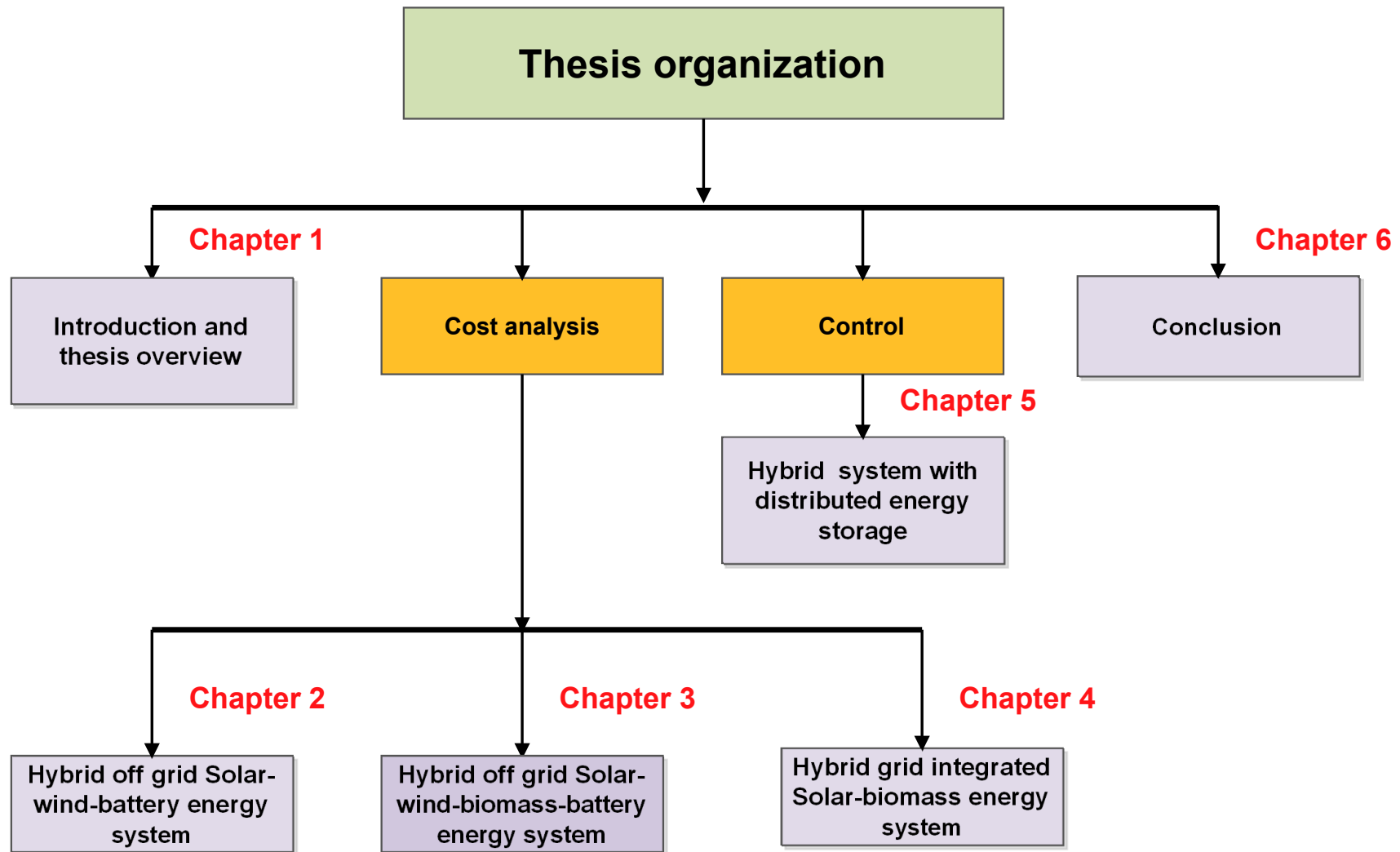
## ABBREVIATIONS

<b>ABC</b>	Artificial bee colony
<b>AC</b>	Alternating current
<b>ACO</b>	Ant colony optimization
<b>AIS</b>	Artificial immune system
<b>ANN</b>	Artificial neural network
<b>ANFIS</b>	Adaptive neuro-fuzzy inference system
<b>ASC</b>	Annualized system cost
<b>BBO</b>	Biogeography based optimizations
<b>COE</b>	Cost of energy
<b>CRF</b>	Capital recovery factor
<b>CS</b>	Charging station/Chaotic search
<b>CUF</b>	Capacity utilization factor
<b>DBC</b>	Droop based controller
<b>DC</b>	Direct current
<b>DE</b>	Differential evolution
<b>DESS</b>	Distributed energy storage system
<b>DG</b>	Diesel generator
<b>DOD</b>	Depth of discharge
<b>EENS</b>	Expected energy not supplied
<b>EIS</b>	Energy index ratio
<b>EP</b>	Evolutionary programming
<b>ES</b>	Evolution strategies
<b>EVs</b>	Electric vehicles
<b>FC</b>	Fuel cell
<b>GA</b>	Genetic algorithm
<b>GW</b>	Gigawatt
<b>HBMO</b>	Honey bee mating optimization

<b>HOMER</b>	Hybrid optimization method for electric renewable
<b>HOGA</b>	Hybrid optimization by genetic algorithm
<b>HS</b>	Harmony search
<b>kW, kWh</b>	kilowatt and kilowatt-hour
<b>LCE</b>	Life cycle emissions
<b>LCOE</b>	Levelized cost of energy
<b>LPSP</b>	Loss of power supply probability
<b>LP</b>	linear programming
<b>MGs</b>	Micro-grids
<b>MILP</b>	Mixed integer linear programming
<b>MPSO</b>	Meta particle swarm optimization
<b>MOGA</b>	Multi-objective genetic algorithm
<b>MW, MWh</b>	Megawatt and megawatt-hour
<b>NPC</b>	Net present cost
<b>PHEV</b>	Plug in hybrid electric vehicle
<b>PSO</b>	Particle swarm optimization
<b>PV</b>	Photo-voltaic
<b>RES</b>	Renewable energy sources
<b>RSM</b>	Response surface methodology
<b>SA</b>	Simulating annealing
<b>SOC</b>	State of charge
<b>TS</b>	Tabu search
<b>WT</b>	Wind turbine

# Nomenclature

$\alpha_p$	temperature coefficient of power	$N_{bg,h}$	biomass gasifier system lifetime (hours)
$\eta_{batt}$	round trip efficiency of the battery	$N_{bg,l}$	life span of the biomass gasifier system (years)
$\eta_{bg}$	efficiency of biomass gasifier system	$N_{bg}$	number of hours biomass system operating during one year
$\eta_{inv}$	efficiency of the inverter	$N_{sol}$	number of solar PV panels
$C_g^p$	cost per unit for purchasing power from the grid	$P_{CS}$	power of charging station
$C_g^s$	cost per unit for selling power to the grid	$P_{bg}^{max}$	maximum rating of biomass gasifier system
$C_{acap}^{bg}$	annualized capital cost of the biomass gasifier system	$P_{gp}^{max}$	maximum power supplied by the grid
$C_{arep}^{bg}$	annualized replacement cost of the biomass gasifier system	$P_{gs}^{max}$	maximum power supplied to the grid
$C_{cap}^{bg}$	capital cost of the biomass gasifier system	$P_L^{max}$	peak load demand at day time ( $kW$ )
$C_f^{bg}$	operational (fuel) cost of biomass gasifier system	$P_{AG}$	power regulation signal
$C_m^{bg}$	maintenance cost of biomass gasifier system	$P_{bg}$	rating of biomass gasifier system
$C_{rep}^{bg}$	replacement cost of the biomass gasifier system	$P_b(t)$	battery's input/output power
$C_{sal}^{bg}$	salvage value of the biomass gasifier system	$P_{dg}$	diesel generator power
$C_{cap}^{sol}$	capital cost of the solar panel	$P_{dump}(t)$	dump energy
$C_{rep}^{sol}$	replacement cost of the component	$P_{fc}$	power generated by FCs
$C_{sal}^{sol}$	salvage cost of the component	$P_{gp}(t)$	power supplied by the grid ( $kW$ )
$C_b$	price of biomass ( $\$/kg$ )	$P_{gs}(t)$	power supplied to the grid ( $kW$ )
$C_{bg}$	annualized total cost of biomass gasifier system (per $kW$ )	$P_{inv}$	rating of inverter
$C_b(Ah)$	single battery capacity	$P_i^{fact}$	participation factor
$C_{gp}$	total price ( $\$/yr$ ) of electricity purchased from grid annually	$P_L(t)$	load demand at any time
$C_{gs}$	total price ( $\$/yr$ ) of electricity sold to the grid annually	$P_{PV}(t)$	total power generated by solar PV panels
$C_{inv}$	annualized total cost of power inverter (per $kW$ )	$P_{rat}$	rated power output capacity of the solar PV panel
$C_{inv}$	annualized total cost of power inverter (per $kW$ )	$P_{sol}(t)$	power generated by single PV panel
$C_{sol}$	annualized total cost of solar PV panel (per $kW$ )	$P_{wt}$	power generated by a single wind turbine
$CV_{bm}$	calorific value of the biomass	$P_w(t)$	total power generated by wind turbines
$E_{bg}$	energy generated by the biomass gasifier system annually	$q(t)$	rate of biomass consumption ( $kg/kWh$ )
$E_{gp}$	energy purchased from the grid annually	$q_1(t)$	hourly fuel (diesel) consumption
$E_{gs}$	energy sold to the grid annually	$r$	interest rate
$f_{loss}$	loss factor of solar PV panel	$SOC_{max}$	maximum state of charge
$G_h$	hourly solar radiation incident on the solar PV panel	$SOC_{min}$	minimum state of charge
$G_S$	standard incident solar radiation	$T_c$	PV cell temperature in the current time step
$k_1, k_2$	fuel curve coefficients	$T_s$	PV cell temperature under standard test conditions
$M_{bg}$	total biomass available ( $Tons/yr$ )	$T_{amb}$	ambient temperature
$n$	lifetime of project in years	$t_{bg}$	number of operating hours of biomass gasifier system in a day
$N_{batt}^s$	number of batteries connected in series	$V_F$	cut off speed
$N_{batt}^m$	maximum number of batteries	$V_{batt}$	voltage of a single battery
$N_{sol}^m$	maximum number of solar PV panels	$V_{bus}$	bus voltage
$N_{wt}^m$	maximum number of wind turbines	$V_C$	cut in speed
$N_{batt}$	the total number of batteries	$V_{err}$	voltage error signal
		$V_R$	rating speed of the wind



# Chapter 1

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## INTRODUCTION AND THESIS OVERVIEW

---

### 1.1 Introduction

Increasing environmental concerns and demands of electricity have compelled an urgent need for alternate energy sources in the world. The available alternate energy sources are solar, wind, biomass, tidal, wave, magneto hydrodynamics generator and small hydro. Out of these available options, solar, wind and biomass energy seem to be more promising towards their nature of inexhaustible, abundant and free availability in the nature. India is a country with a huge potential for renewable energy due to its geographical location. In India, the percentage of renewable power generation has been increased significantly in past few years. [Figure 1.1](#) shows the total installed capacities of India source wise as on 31st July, 2016. In 2016, India's total installed power generation capacity has been reached to 304 *GW*. The major contribution comes from combustion of fossil fuel, which is almost 70% of the entire generation. [Figure 1.2](#) depicts percentage wise contribution of energy sources in Indian power sector.

In the last decade, renewable grid capacity as a percentage of total capacity has been increased by almost six times. As on 31st July, 2016 total renewable power generation capacity has reached 44,812 *MW*, which is about 14% of the total installed capacity of 304 *GW*. The major contribution comes from wind energy which is 27,441 *MW*. Total contribution from renewable technologies is increasing in rapid manner and also research and technology to utilize renewable is making progress [[MNRE \(2016\)](#)].

[Table 1.1](#) shows a detailed break up of grid-interactive power in India in 2016 by renewable power sources. It is evident that in India, a total 44,812 *MW* of power generation from renewable energy sources is grid integrated. Besides, India has some off grid/captive power generation of 1,347 *MW* as shown in [Table 1.2](#). The biomass power generation has a

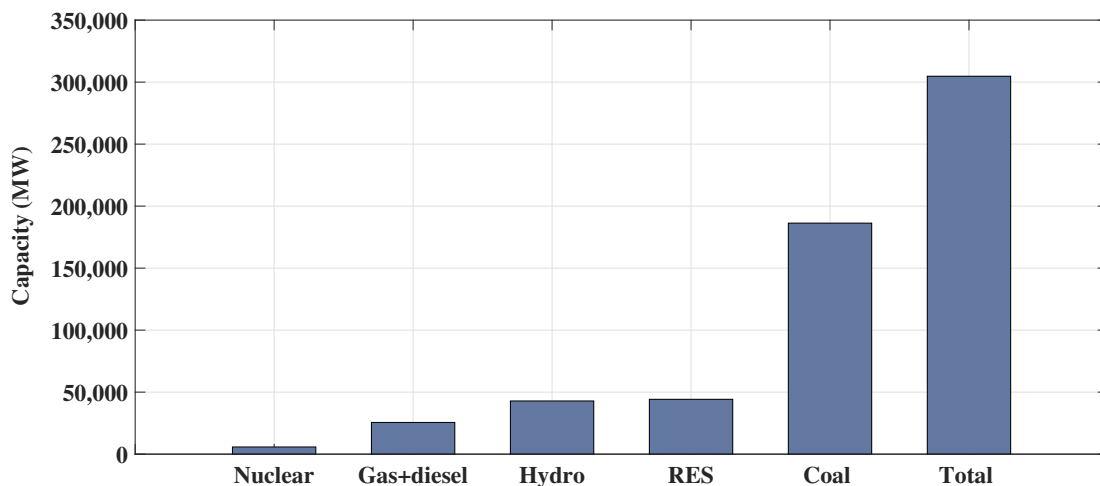


Figure 1.1: Indian power sector at a glance in the year 2016

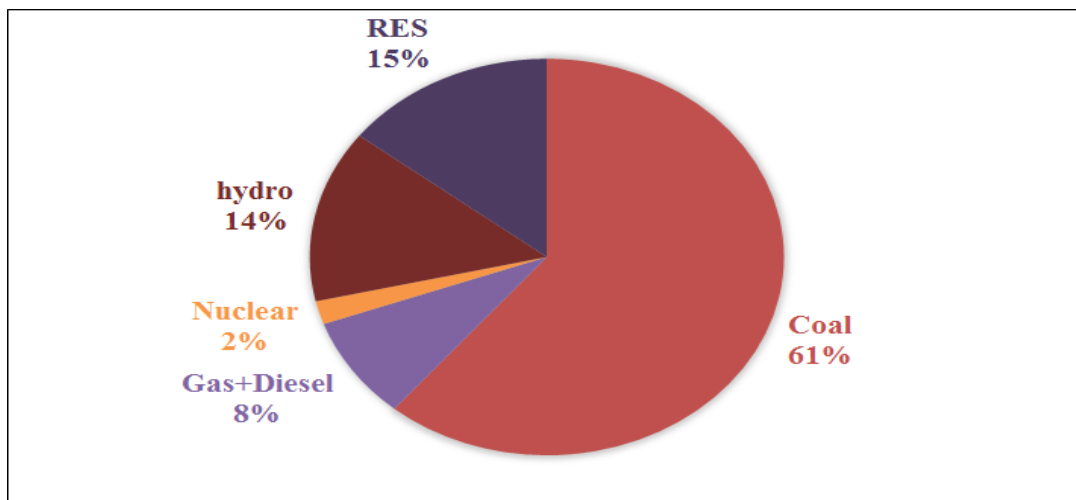


Figure 1.2: Percentage share of energy sources in Indian power sector in the year 2016

major contribution in off grid power generation. According to ministry of power, India, almost 5% of the total villages still do not possess access to electricity and mostly electrified villages face scarcity of electricity, especially in summer when electrical demand is at peak [Ministry of Power (2016)]. In India, the primary focus is on restructuring of power system to improve the quality of power and efficiency of the existing electrical power network [Thakur *et al.* (2006)].

Renewable energy systems (RESs) are proving to be reliable, promising and environmental friendly source of electricity generation. Renewable based energy systems are gaining popularity to meet the electricity demand of remote or off grid locations due to technological improvement in renewable based technologies and environmental concerns [Deshmukh and Deshmukh (2008)]. The use of renewable energy sources have significantly increased as decen-

Table 1.1: Grid-interactive renewable power in India (Capacities in *MW*)

S.No.	Source	Power ( <i>MW</i> )
1	Wind power	27,441.15
2	Solar power	8,062.00
3	Small hydro power	4,304.25
4	BioPower (Biomass, Gasification and Bagasse Co-generation)	4,882.33
5	Waste to power	122.58
	<b>Total</b>	<b>44,812.31</b>

Table 1.2: Off-grid/captive renewable power in India (Capacities in *MW*)

S.No.	Source	Power ( <i>MW</i> )
1	Waste to energy	161.39
2	Biomass (non-bagasse) Co-generation	651.91
3	Biomass gasifiers (Rural+Industrial)	192.39
4	Aero-generators /Hybrid systems	2.79
5	SPV systems	330.00
6	Water mills /micro hydel	18.81
	<b>Total</b>	<b>1,347.29</b>

tralized systems. A recent trends shows that installations of RESs, particularly in developing countries is increasing significantly [Akella *et al.* (2009)]. Renewable based power generation will be a a viable option for environmentally sound energy production in near future [Kaul and Edinger (2004)]. Standalone photovoltaic (PV) system with backup and storage are proposed and successfully developed by various researchers. The stand-alone PV system is a very attractive method to provide electricity to the places like remote or off grid locations [Khatib *et al.* (2012), Nfah (2013), Rehman *et al.* (2012), Yamegueu *et al.* (2011)], isolated islands [Bala and Siddiqui (2009), Phuangpornpitak and Kumar (2011)], street lighting [Lagorse *et al.* (2009)], tourist place [Bakos and Soursos (2002)], remote communication center [Ashenayi and Ramakumar (1986)] and commercial building [Shaahid and Elhadidy (2004)].

The PV generation has low energy conversion efficiency and the cost of electricity per *kWh* is costlier than wind power [Senjyu *et al.* (2005)]. Therefore, wind generation system has attracted a lot of attention. Elhadidy and Shaahid (2004) investigated a wind-diesel based system in meeting load requirement of a commercial building in Dehran, Saudi Arabia. A general model of wind-diesel based system was proposed by Hu and Solana (2013). Abouzahr and Ramakumar (1990, 1991) investigated standalone wind energy conversion system for grid utility. Wind energy is proving to be a clean and new promising source of power generation.

However, integration of wind energy into the existing electricity grid creating reliability and stability issues [[Singh and Singh \(2011\)](#)].

The solar and wind resources are unpredictable in nature and the major concern in the designing of a standalone wind or solar system is the reliability of the system. Therefore, integrating two resources in hybrid system (wind-solar) can mitigate this problem up to some extent. One's weakness can be compensated by the strengths of the other, but that increases the complexity of the system. Integration of two or more options in hybrid system is hard to analyze [[Nehrir et al. \(2011\)](#)]. Utilization of hybrid sources becomes increasingly significant, attractive and cost effective options for power in remote or off grid locations [[Ashenayi and Ramakumar \(1986\)](#), [Ramakumar et al. \(1986\)](#), [Swift and Holder \(1988\)](#)]. Different scenarios of integrated hybrid renewable systems to supply electricity in the rural areas of Uttarakhand, India have been investigated by [Patil et al. \(2010\)](#) and [Patil et al. \(2011\)](#). [Elhadidy and Shaahid \(1998, 2000, 2003\)](#) promoted different hybrid options of renewable energy in energy efficient regions. It is proven that these hybrid systems provide reliable and low price electricity to the consumer, especially in rural or off grid locations. However, integration of renewable energy resources into existing systems is a challenging task [[George and Banerjee \(2011\)](#)].

A generalized and simple block diagram of a hybrid renewable energy based system with storage is demonstrated in [Figure 1.3](#). This system is termed as a hybrid coupled hybrid configuration [[Siddaiah and Saini \(2016\)](#)]. In this type of configuration, RESs which generates AC such as wind turbines, biomass gasifier etc. are directly connected to AC bus, while the RESs which generates DC such as solar panels are connected through a converter to the DC bus. The energy storage system such as battery bank is connected to DC bus and can supply load on the AC bus by using a bi-directional converter. This configuration is more complex as it has both AC and DC components. Moreover, a diesel generator can also be connected to AC bus. A hybrid system can be connected to the grid via an optional switch. This types of hybrid configuration is more complex than the AC and DC coupled configurations. Control and power management in these type of configurations is a challenging job. Two major factors associated with the hybrid systems are price of electricity and reliability of the system. An optimal system design must be economical and reliable, and it can be achieved with the help of proper selection of components of the system. Thus an optimal sizing method is necessary to design an efficient and economical hybrid system. Many conventional, non-conventional, hybrids, multi-objective

methods have been applied by various researchers for cost analysis and power management of the hybrid system. Apart from these techniques, various software tools have been designed for system sizing. In next section, a detailed review on optimization method used for designing renewable based hybrid system have been carried out.

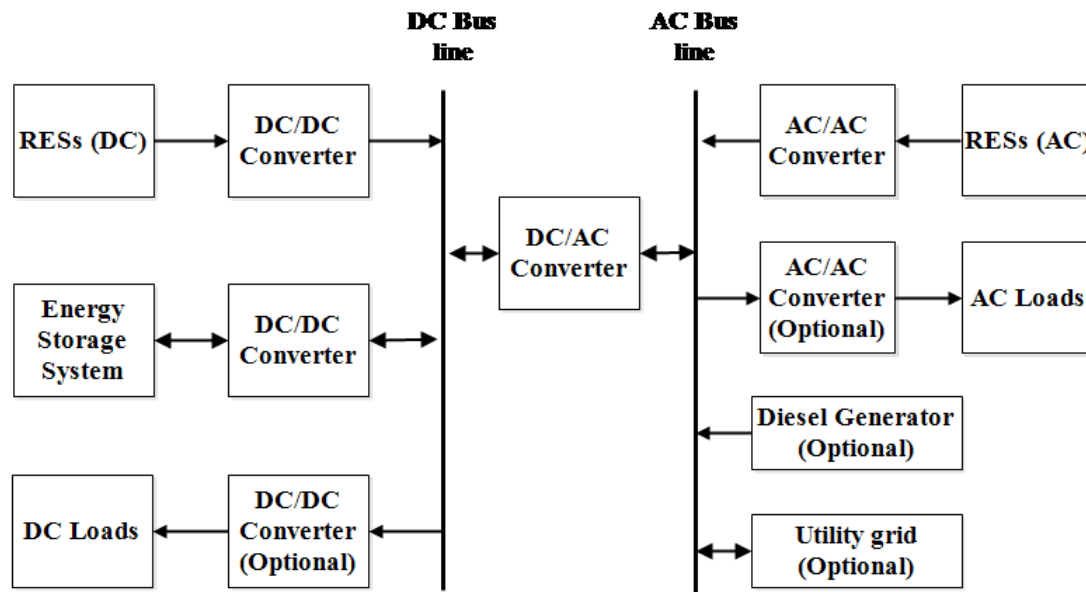


Figure 1.3: Different components of a hybrid coupled configuration

## 1.2 Optimization methods applied to hybrid system

The main objective in designing of a hybrid system is proper selection of components while minimizing the total net present cost (NPC) of the project. Proper selection of components leads to a reliable system. The total NPC of the system includes purchasing, installations, operations, maintenance and replacement costs of the components. The designed system must be optimal in terms of cost and reliability. For cost analysis, major terms such as NPC, annualized system cost (ASC), levelized cost of energy (LCOE) or the cost of energy (COE) is employed. Reliability is measured by several factors such as loss of power supply probability (LPSP), expected energy not supplied (EENS), energy index ratio (EIS) and life cycle emissions (LCE).

Figure 1.4 demonstrates a simplified flow chart of the optimization steps followed in case a general hybrid renewable based energy system. The input resource data can be collected by measuring real time on site or data can be collected from various websites. The component costs and optimization algorithm selection are major parameters. In single objective function,

the main objective is the total cost of the system, while in multi-objective function, the other objectives such as unmet load and pollutant ( $CO_2$ ) emissions could be considered. As compared to a single objective, multi-objective is a complex problem due to the conflicting natures of the objectives. In recent years, to calculate the optimum configuration various optimization methods and tools have been developed and successfully applied in numerous publications. Along with conventional techniques, many meta-heuristic algorithms and hybrid techniques have been successfully implemented for the system sizing. In this work, optimization sizing methods are broadly classified into four categories, i.e., software tools, conventional, non-conventional and hybrid methods. A broad classification of optimization methods is demonstrated in [Figure 1.5](#).

### 1.3 Optimization software tools

Various software tools and programs are nowadays available for analyzing and designing of renewable based energy systems. These tools are now commercially available and most of the tools are open source. It is found in the literature that there are more than 50 software tools available. A detailed study of these tools can be found in [[Connolly \*et al.\* \(2010\)](#), [Sinha and Chandel \(2014\)](#)]. It is inferred from the literature that most applied software tools found in the literature are HOMER (Hybrid optimization method for electric renewable) and HOGA (Hybrid optimization by genetic algorithm). HOMER simulates various renewable energy source system configurations and shorted them on the basis of the NPC. HOMER is basically an optimization software tool developed by the national renewable energy laboratory (USA), which simulates various renewable energy source system configurations and scales them on the basis of the NPC which is the total cost of installing and operating and maintain the system over its lifetime. It can be downloaded freely from (<http://www.nrel.gov/homer>), and more than one lakh downloads have been attained. One day training on HOMER would be enough to run a typical analysis. HOMER facilitates the design of electric power system for stand alone and also for grid connection applications for optimization and sensitivity analysis. The available components in HOMER are wind turbines, PV arrays, run-of river hydropower, biomass power, internal combustion engine generator, micro turbine, fuel cells, batteries and hydrogen storage. It also includes all cost (except any pollution penalty). The inputs required for simulation are energy resources, economics and technological constraints, energy storage requirement

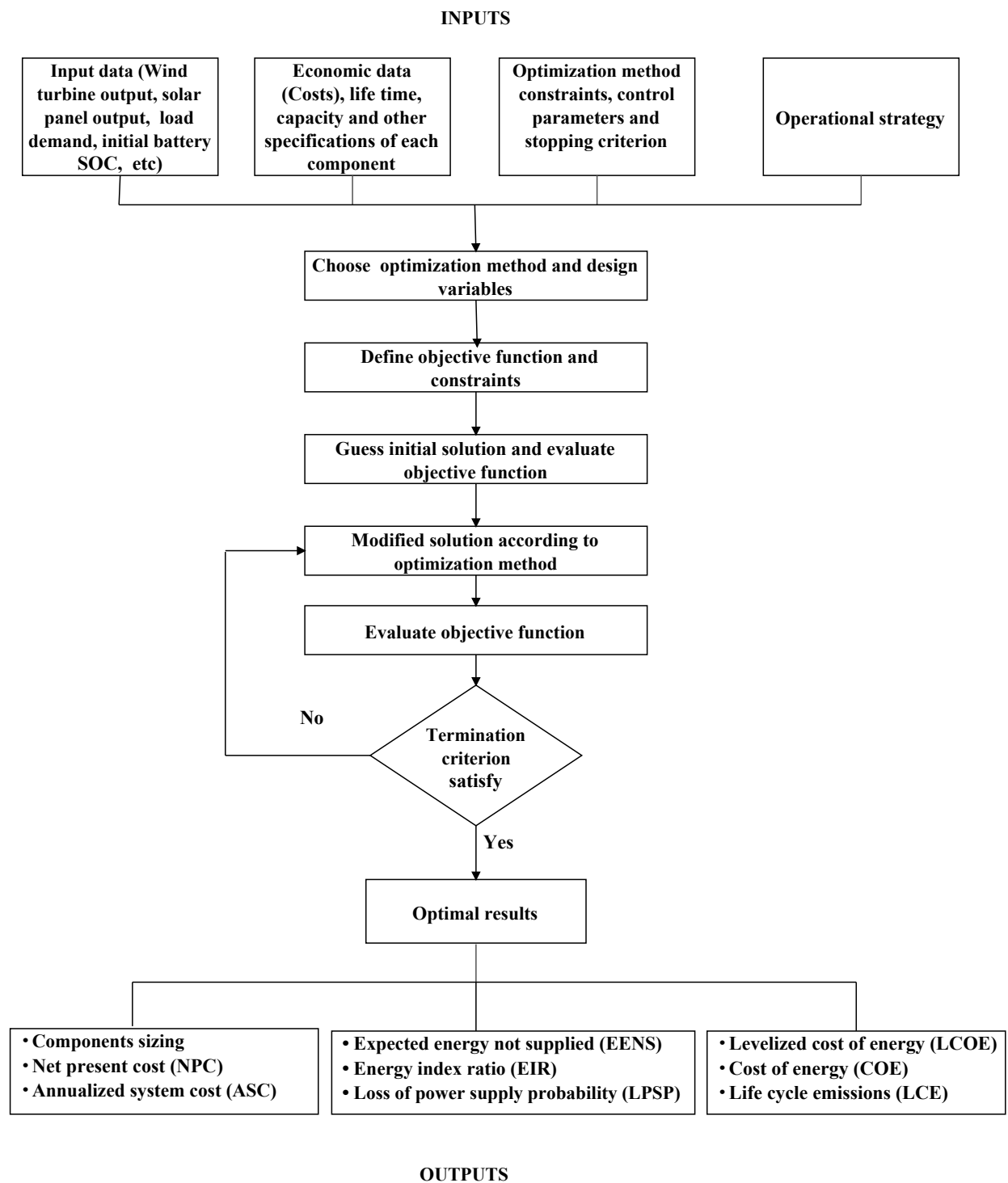


Figure 1.4: Generalized steps followed in the optimization of hybrid renewable energy systems

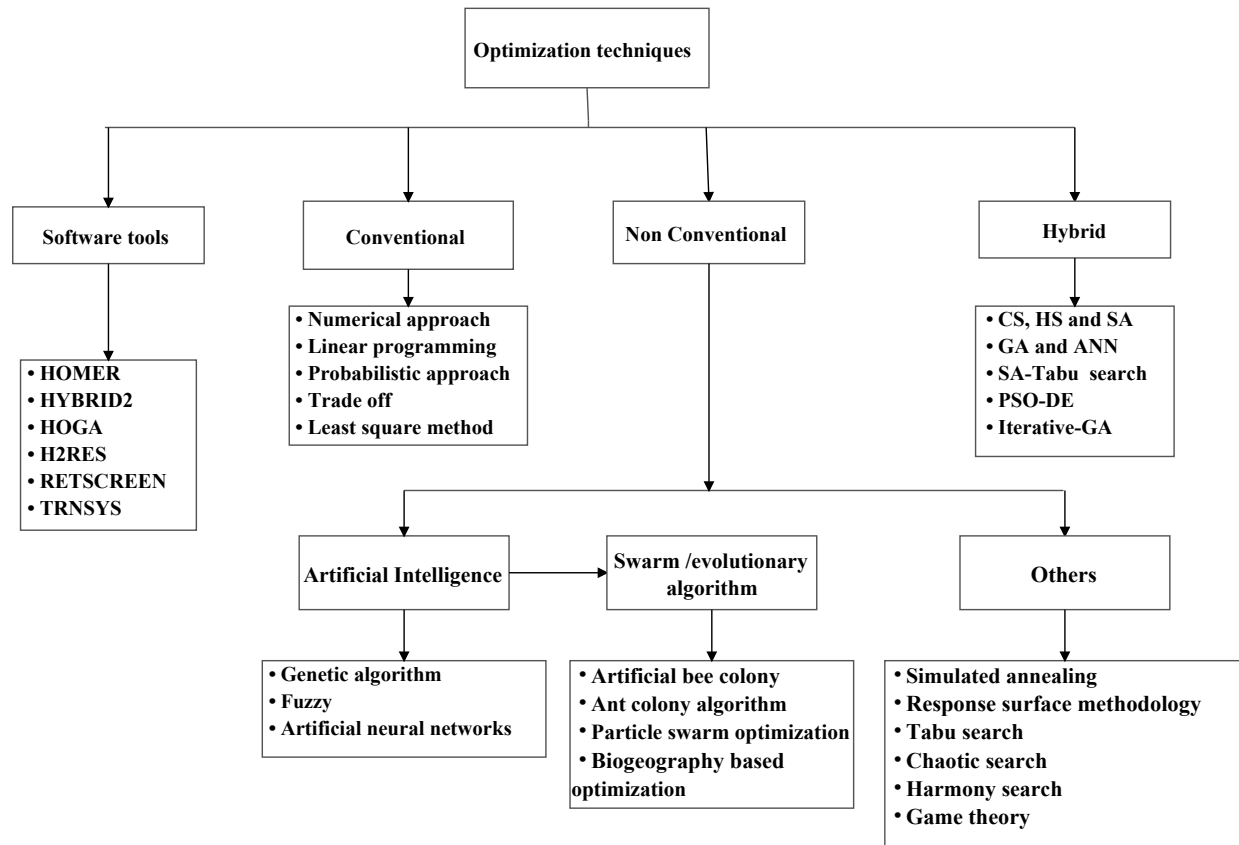


Figure 1.5: A broad classification of optimization techniques

and system control strategies. The other input like component type, capital cost, maintenance and operational cost, replacement cost, efficiency, life of the project etc. can be provided by a user for simulation. HOMER algorithm considers each possible combination that can satisfy the load requirement and satisfy other constraints. In the result all feasible optimized solution is displayed by according to NPC of the hybrid system. A list of such publications (year wise) that involved HOMER in the last few years is demonstrated in [Table 1.3](#).

The other useful design tool with multi-objective capability to design hybrid power system is HOGA. It is a simulation and optimization program developed by Rodolfo Dufo Lopez and Jos Luis Bernal Agust n of University of Zaragoza. It uses C++ platforms for hybrid renewable systems for generation of electrical energy. It can be freely downloaded from the website ([www.hoga-renewbale.es.tl](http://www.hoga-renewbale.es.tl)). The multi objective optimization (LCOE,  $CO_2$  emissions and unmet load) system can be designed by HOGA. The main components included in HOGA are PV panels, wind turbines, hydraulic turbines, Fuel cells (FC),  $H_2$  tanks, batteries, inverters, rectifiers, and AC generators etc. It provides flexibility to the users to choose their own hybrid system. The multi objective optimization (LCOE,  $CO_2$  emissions and unmet load)

system can be designed by HOGA. It provides flexibility to the users to choose their own hybrid system [Bernal-Agustin and Dufo-Lopez (2009)]. HOGA has been applied by various researcher such as Castañeda *et al.* (2012), and Dufo-lópez and Bernal-agustín (2012).

Apart from these few more software tools such as hybrid power system simulation model (HYBRID2) [Mills and Al-Hallaj (2004), Panahandeh *et al.* (2011)], Matlab-simulink optimization tool [Dihrab and Sopian (2010), Koussa *et al.* (2011)], Integrated renewable energy optimization model (IREOM) [Patil *et al.* (2011)]. TRNSYS [Panayiotou *et al.* (2012)], adaptive neuro-fuzzy inference system (ANFIS) [Buasri and Salameh (2007), Rajkumar *et al.* (2011)], Dividing rectangles algorithm (DIRECT) [Belfkira *et al.* (2008), Belfkira *et al.* (2011)], Opt quest [Ekren *et al.* (2009)] and RETScreen [Liqun and Chunxia (2013)] have been found in literature. The major disadvantages of the software tools are their black box coding and more computational time. The other disadvantages include limitation of optimal function, intra-hour variability and complex constraint handling. However, these tools have some advantages such as user friendly and easy to use. A large number of technology options are available in these tools and some tools can also perform sensitivity analysis of different parameters.

## 1.4 Conventional techniques

Different conventional methods are applied to obtain the optimal configurations of the hybrid energy systems. The methods applied by various authors are graphical construction method, least square method, iterative and probabilistic approaches, linear programing (LP) and mixed integer linear programming (MILP). These techniques are simple to use, easy to understand and possess a wide range of applicability. The literature and brief introduction of the techniques is discussed in following section.

### 1.4.1 Iterative technique

An iterative approach is a recursive process that improves the quality of available solutions until a termination criterion is satisfied. The improvement in quality of solution can either minimize or maximize the objective function of the problem. Kellogg *et al.* (1996) used a simple iterative optimization method to detect the optimal size of wind and PV module for a standalone hybrid system. Later on, same authors Kellogg *et al.* (1998) applied the simple iterative method to

Table 1.3: Publication in literature using software tool HOMER

Reference	Hybrid components	Place/country	Remark/application
Khan and Iqbal (2005)	Wind-PV-diesel-Fuel cell-batteries	Newfoundland /Canada	Design to supply load of remote house as the stand-alone load
Razak <i>et al.</i> (2007)	Pico-hydro-wind-PV-diesel-batteries	Malaysia	Theoretical load, minimize excess energy
Nandi and Ghosh (2009)	Wind-PV-batteries	Sitakunda /Bangladesh	Design for off-grid location, load of 120 house considered, CHG analyses also presented
Panapakidis <i>et al.</i> (2009)	Wind-PV-diesel-FC-batteries	Greece	Design for a residential load/grid independent
Hrayshat (2009)	PV-diesel-battery	Jordan	Design for a off-grid house, located in a remote Jordanian settlement
Bekele and Palm (2010)	Wind-PV-diesel-battery	Ethopia	Designed for remotely located model colony of 200 families.
Nandi and Ghosh (2010)	Wind-PV-diesel-battery	Bangladesh	For a island in Bangladesh, CHG analysis also considered
Patil <i>et al.</i> (2010)	MHP-biomass-biogas-wind-SPV	India	Discuss different hybrid scenario of seven remote village
Haidar <i>et al.</i> (2011)	Wind-PV-diesel-battery	Malaysia	Design for a load of 5.8 kW households
Türkay and Telli (2011)	Wind-PV-FC-grid	Turkey	Design for a load of 150 kW
Bekele and Tadesse (2012)	Wind-PV-Hydro-diesel-batteries	Ethiopia	Consider six sites in Ethiopia
Sureshkumar <i>et al.</i> (2012)	Wind-PV-batteries	India	1.989 kWh/d, 207 kW load
Hafez and Bhattacharya (2012)	Wind-PV-hydro-diesel-batteries	Canada	Deign for a load of 5000 kWh/d and 1183 peak demand
Bekele and Tadesse (2012)	Wind-PV-hydro-diesel-batteries	Ethiopia	Consider six site in Ethiopia
Badawe <i>et al.</i> (2012)	Wind-PV-diesel-batteries	Canada	Deign to provide power to a microwave repeaters in a location in Canada.
Rehman <i>et al.</i> (2012)	Wind-PV-diesel	Saudi Arabia	Design for a village having load demand of 17043.4 MWh/yr
Askari and Ameri (2012)	Wind-PV-diesel-battery	Kerman, Iran	Design for a 50 typical rural household for a peak load demand 11 kW
Dorji <i>et al.</i> (2012)	Wind-PV-diesel-battery	Bhutan	Design for a 4 different location in rural Bhutan
Ashourian <i>et al.</i> (2013)	Wind-PV-Fuel cell-Diesel -batteries	Malaysia	Demand of an island resort in Malaysia
Guler <i>et al.</i> (2013)	Wind-PV-battery-grid	Turkey	Demand of an small hotel in Turkey
Hiendro <i>et al.</i> (2013)	Wind-PV	Indonesia	Design for a remote location
Hassiba <i>et al.</i> (2013)	Wind-PV-diesel-batteries	Algeria	Load of a telecommunication system, 2 kWh/d, average 339 W
Dursun <i>et al.</i> (2013)	Wind-PV-diesel-battery	Turkey	1853 kWh/d, isolated load
Li <i>et al.</i> (2013)	Wind-PV-Diesel	China	For a household in china, variation of tilt angle also considered
Sen and Bhattacharyya (2014)	Wind-PV-biodiesel-smallhydro-battery	India	For three load profile in a off grid village in India
Bhattacharjee and Acharya (2015)	Wind-PV-battery	India	Design for 1.4kW load in low wind topology
Sinha and Chandel (2015), Sinha and Chandel (2016)	PV-micro-wind-battery	India	Design for a institutional area
Mamaghani <i>et al.</i> (2016)	Wind-PV-battery-diesel	Columbia	Design for three off grid villages in Columbia

design a hybrid wind and PV generating system based on energy balance. [Yang, H.X. \*et al.\* \(2003\)](#) investigated an iterative optimization technique based on the LPSP model for a hybrid solar-wind system. [Ashok \(2007\)](#) developed a general constraint optimization model based on quasi-newton algorithm to find out component sizing of community-based hybrid energy systems. The author considered load demand of small village in Indian scenario. [Muselli \*et al.\* \(1999\)](#) proposed optimal configuration of a hybrid system which guaranteed minimum cost of energy per *kWh*. [Kaabeche \*et al.\* \(2011\)](#) also applied iterative technique to find out the component sizing of hybrid PV-wind-battery system. The authors also considered issues like LPSP and LCOE. [Diaf \*et al.\* \(2007\)](#) proposed an independent hybrid PV-wind system to supply power to residential area of Corsica Island by considering LPSP and LCOE. [Ai \*et al.\* \(2003\)](#) developed a LPSP based method to deduce component sizing of PV-wind hybrid system. [Celik \(2003\)](#) presented technical and economic analysis of an off-grid hybrid PV-wind energy system.

### 1.4.2 Linear programming

Linear programming is used to solve continuous and discrete variable based mathematical and engineering problems. [Ramakumar \*et al.\* \(1986\)](#) proposed LP technique for the design of integrated renewable energy systems. A similar LP model was used to detect an optimal mix of wind and PV for system design by [Swift and Holder \(1988\)](#). [Chedid and Rahman \(1997\)](#) proposed LP techniques to minimize the price of electricity ensuring the reliability of the power of a hybrid wind solar system. [Ulgen and Hepbasli \(2003\)](#) investigated the optimum solar and wind combination of a hybrid system for Izmir, Turkey. [Ferrer-Marti \*et al.\* \(2013\)](#) proposed a MILP model for optimal hybrid wind-PV systems that solves the location of the wind-PV generators and the design of the micro grids. [Malheiro \*et al.\* \(2015\)](#) proposed a hybrid system consists of solar, wind and batteries for a location in Portugal. The optimal sizing of the components is achieved with MILP to minimize the LCOE. In conventional methods LP and MILP programming are widely used as optimal techniques.

### 1.4.3 Graphical construction method

[Markvart T. \(1996\)](#) discussed applicability of a simple graphical constructional technique to design an optimal PV-wind energy system. The authors proposed system for a location in the UK that satisfies energy demand of users throughout the year. [Borowy and Salameh \(1996\)](#)

used a graphical construction technique to calculate size of the battery bank and PV array in a hybrid solar-wind system. The similar simple graphical method was also applied by [Eke \*et al.\* \(2005\)](#) to find out the solar-wind sizing of a hybrid system that fulfills the electricity needs of the Solar Energy Institute of Ege University in Izmir, Turkey.

### 1.4.4 Least square method

[Borowy and Salameh \(1994\)](#) developed a simple algorithm to find the optimum number of PV arrays for a standalone hybrid system. The output of PV module and wind turbine was calculated on the basis of probability density function. The authors used least square method to determine the best fit of PV array while keeping wind turbine fixed. Later on, same authors [Borowy and Salameh \(1996\)](#) developed a methodology to find out the capacity of the battery bank and rating of PV array for an off-grid hybrid wind-PV system. The authors developed an algorithm to get the desired LPSP while keeping the cost of system minimum. [Gomma \*et al.\* \(1995\)](#) also applied the least square method to find out the optimal number of PV and wind turbines for a site in Egypt.

### 1.4.5 Probabilistic approach

[Bagul \*et al.\* \(1996\)](#) developed a methodology by using a three event probabilistic approach for sizing of a wind-PV system. [Karaki \*et al.\* \(1999\)](#) described a general probabilistic model of a standalone hybrid system. Electrical load was managed with the help of solar park, wind turbines and batteries. [Tina, G., Gaglianom S., Raiti \(2006\)](#) evaluates long term performances of off grid and grid integrated hybrid solar-wind system based on convolution technique based probabilistic approach.

### 1.4.6 Others techniques

There are some other traditional methods such as monte-carlo-simulation [[Billinton and Karki \(2001\)](#)], branch and bound [[Geem \(2012\)](#)], trade off [[Gavanidou and Bakirtzis \(1992\)](#)] etc. have been successfully applied by various researchers. The drawback and limitations of above mentioned conventional techniques are that they are often trapped in local optima especially when applied to non-linear objective function or when numbers of variables are more. To

overcome this problem, various modern optimization techniques, which are based on biological evolution or swarm behavior in colonies are getting attention.

## 1.5 Non-conventional optimization techniques

Large scale engineering optimization problems have created need of alternative optimization techniques. Particularly, bio-inspired evolutionary algorithms are applied to large scale optimization problems to achieve an optimum solution with less computational simplicity. These algorithms are inspired by natural evolution or social behavior of the species. Various researches have applied numerous optimization techniques i.e. artificial neural network (ANN), particle swarm optimization (PSO), genetic algorithm (GA), ant colony optimization (ACO), differential evolution (DE), evolutionary programming (EP), evolution strategies (ES), biogeography based optimizations (BBO), artificial bee colony (ABC), honey bee mating optimization (HBMO), artificial immune system (AIS), harmony search (HS), tabu search (TS), simulating annealing (SA) and variant of these techniques [Erdinc and Uzunoglu (2012), Zheng *et al.* (2013), Zhou *et al.* (2010)]. Some of the recent global optimization techniques applied to solve sizing problem of hybrid solar-wind systems are discussed in brief in following section.

### 1.5.1 Genetic algorithm

GA was the first evolutionary based optimization technique. GA was developed by John Holland of University of Michigan in 1975. It is a global search algorithm inspired by the mechanics of biological evolution. It is based on Darwin's "Survival of the fittest" concept. GA is totally different from conventional method. It has been successfully applied in various engineering optimization problems and able to provide global optimum results in both single and multi-objective optimization problems [Holland (1975)]. In case of hybrid renewable based system, GA is applied to deduce the components sizing while minimizing total NPC of the hybrid system. Numerous researches have reported on GA in the optimization of hybrid wind-solar system.

Seeling-Hochmuth (1997) applied GA to the operational control of PV-hybrid energy systems. Xu *et al.* (2005) proposed optimal size methodology of components of a standalone hybrid wind-PV power system by using GA. The total capital cost was minimized subject to

the constraint of the LPSP. [Koutroulis \*et al.\* \(2006\)](#) deduced optimal sizing of a standalone PV-wind generation by applying GA. [Senjyu \*et al.\* \(2007\)](#) used GA to find out the optimal configuration of hybrid (wind-PV) with batteries and backup system in three isolated islands in Japan. [Yang \*et al.\* \(2008\)](#) proposed an off grid PV-wind based system to supply power for a telecommunication relay station to achieve required LPSP. The ASC was minimized with the help of GA. [Hongxing \*et al.\* \(2009\)](#) analyzed a GA based optimal design model for designing hybrid solar-wind systems for a telecommunication relay station in China and ensured minimized annualized cost of the systems while satisfying required LPSP. [Gupta \*et al.\* \(2009\)](#) and [Gupta \*et al.\* \(2012\)](#) developed a novel control scheme optimized through GA for the control of standalone hybrid solar wind system. [Tudu \*et al.\* \(2011\)](#) compared between GA and PSO techniques for unit size of hybrid energy systems. [Poullikkas \*et al.\* \(2011\)](#) developed a GA based optimum model for integration of renewable energy technologies into the power system. The reliability and optimal sizing have been discussed by [Nafeh \(2011\)](#). The author used GA technique to optimize two purposes, i.e., one the cost function of the total hybrid system and another to serve load according to reliability criteria by keeping LPSP minimum.

[Bilal \*et al.\* \(2012\)](#) implemented GA techniques to calculate the optimum size of a standalone hybrid wind-PV system for two places in Senegal. [Merei \*et al.\* \(2013\)](#) proposed a hybrid system for a telecommunication sites in Syria. By using GA, component sizes were determined to minimize the overall costs. [Chen \(2013\)](#) applied an advanced version of GA, adaptive GA to detect size of a stand-alone hybrid wind-PV with batteries generation system for two sites in Taiwan. Two major factors considered were the cost of the system and the reliability. [Al-shamma and Addoweesh \(2014\)](#) proposed techno-economic analysis of a small hybrid system by using GA. The system was proposed to meet load requirement of a small village in Saudi Arabia. [González \*et al.\* \(2015\)](#) applied a GA based toolbox in MATLAB to find optimal sizing of grid integrated hybrid solar-wind energy system. The system was implemented on real time hourly wind and solar irradiation data and electricity demand from rural township in the central Catalonia, Spain.

### 1.5.2 Particle swarm optimization

In 1995, Eberhart and Kennedy proposed a new stochastic optimization method based on social behavior of a flock of migrating birds or fish schooling. Each possible solution of any problem is

termed as a particle in PSO. Each particle updates its position according to its own (local search) experience as well as the experience of other (global search) particles. PSO has proven a better computational efficiency when applied to real time problems. Wang and Singh (2009) used a modified multi-objective PSO (MOPSO) designed a hybrid system on the basis of cost and reliability. System uncertainties, such as load or generation variations were also incorporated in the system.

Kaviani *et al.* (2009) proposed an advanced version of PSO to minimize total NPC of a wind-PV-FC hybrid system. Outage probabilities of three components, i.e. Wind turbine, PV arrays and DC-AC converter were also considered in the project to ensure the reliability of the system. Hakimi and Moghaddas-Tafreshi (2009) discussed optimal sizing and operational strategy based on PSO for hybrid systems. Phuangpornpitak *et al.* (2010) discussed applications of PSO in different renewable energy sources and reviewed different publications based on PSO on renewable energy sources. Amer *et al.* (2013) proposed an optimal hybrid renewable energy system to fulfill load demand of typical house using PSO. Paliwal *et al.* (2014) applied PSO for optimal component sizing for a hybrid model which comprised of diesel, PV, wind and battery storage.

With the advancement in computational technology, several modified and advanced version of PSO has been proposed by various researchers. Zhao *et al.* (2009) applied improved version of PSO algorithm for a standalone wind-PV hybrid system. Bansal *et al.* (2011) proposed a modified PSO i.e. Meta particle swarm optimization (MPSO) for optimization of hybrid PV-wind-energy system. Jidong Wang (2013) applied modified PSO for a standalone wind-solar-battery hybrid power system, taking into account the power reliability and cost of the total system. Hassan *et al.* (2015) applied modified PSO to design the optimal system to fulfill the load demand of Mansoura University, Egypt. Maleki *et al.* (2015) implemented different variants of PSO on optimal sizing of hybrid system situated at Iran. The authors compared results of different variants of PSO to other techniques such as SA, TS and HS. Khare *et al.* (2015) applied chaotic particle swarm optimization (CPSO) to find out component sizing of a hybrid system and results obtained were compared to HOMER and PSO. It is found that CPSO outperforms PSO and HOMER.

### 1.5.3 Biogeography based optimization

Biogeography deals with the study of the geographical distribution of biological organisms. By inspiring natural biogeography, Simon proposed population based evolutionary algorithm named BBO. It has almost the same features as other bio based optimization techniques such as PSO and GA. So it can be applied to the same type of problems where GA and PSO are applicable. BBO has a fast convergence rate due to lesser computational steps per iteration. [Bansal \*et al.\* \(2013\)](#) developed a BBO based algorithm for prediction of small size autonomous hybrid power systems in remote areas. The power options considered by the authors were wind, solar and small hydro. The results were compared with other optimization techniques and it is observed that BBO provides less computational time with better convergence property. [Kumar \*et al.\* \(2013\)](#) implemented BBO algorithm to evaluate optimum component sizes and operational strategy of a hybrid PV-wind system. It is also observed that BBO possess some good convergence property as compared to other techniques such as PSO, CLPSO and GA.

### 1.5.4 Ant colony optimization

ACO was introduced by Dorigo and his colleagues in 1992. Like PSO, it is also a social behavior based algorithm. It is inspired from the behaviors of ants in real ant colonies. It is evident that ants can find the shortest path between nests and food source. The ants have a particular method to communicate among themselves called pheromones trails. The ants left pheromones while walking on a path. Pheromone quantity increases, according to food quantity. The stronger the smell of pheromone, the larger is the number of attracted ants to go on that path. Other ants go to food source according to pheromone trails. It is a comparatively latest approach and has attracted attention of researchers [[Dorigo \*et al.\* \(1996\)](#), [Dorigo \*et al.\* \(2006\)](#)].

[Xu \*et al.\* \(2006\)](#) implemented a specific graph based ant system to design off grid hybrid wind-PV system. Total NPC was minimized subject to the constraint of the LPSP. [Tra-zouei \*et al.\* \(2013\)](#) implemented ACO and PSO algorithm for optimal design of a standalone wind-solar with diesel system. Authors minimized the NPC of the system for life time considering the loss of probability index. ACO is a new promising technique for future applications and may be applied to various hybrid system sizing studies. The ACO can be helpful for upcoming research on hybrid system and may be applied to similar kind of optimization problem

where PSO and GA have been applied.

### 1.5.5 Artificial bee colony algorithm

The ABC is inspired by social behaviors of honey bee swarm. ABC is a competitive recently developed algorithms by Dervis Karaboga and Basturk in 2005. ABC is inspired by the intelligent behavior of honey bees and it can be applied to all types of optimization problems. [Javadi \*et al.\* \(2011\)](#) designed a battery based hybrid wind-PV system by using an artificial bee colony algorithm to meet the power demand of a residential area. [Govardhan and Roy \(2012\)](#) applied artificial bee algorithm and other techniques for optimal scheduling of a practical system of 24 hours load demand to minimize operating cost of micro-grid. [Mahmood \*et al.\* \(2014\)](#) applied ABC to find out size of PV panel, charger and battery in a system. Further, the results were compared with GA and it is found that ABC algorithm performs adequately. [Maleki \*et al.\* \(2015\)](#), [Maleki and Pourfayaz \(2015\)](#) modeled a hybrid system with the help of different evolutionary algorithms. It is found that the ABC algorithm provides competitive results as compared to PSO, SA and TS.

### 1.5.6 Simulated annealing

SA is a general optimization technique introduced by Kirkpatrick based on annealing process in metallurgy [[Kirkpatrick \*et al.\* \(1983\)](#)]. [Ekren and Ekren \(2010\)](#) proposed an SA algorithm to calculate total NPC of a hybrid PV-wind along with battery system in Turkey. The results were compared with response surface methodology (RSM) previously applied by [[Ekren and Ekren \(2008\)](#), [Ekren and Ekren \(2009\)](#)]. It is found that SA predicts better results as compared to RSM technique. [Agarwal \*et al.\* \(2012\)](#) implemented SA to achieve the optimal size of a hybrid solar-diesel-battery based energy system. The applicability of SA technique needs further attention in research.

### 1.5.7 Others techniques

With the advancement in new algorithm, in the last few years several more non conventional approaches have been implemented in solar-wind hybrid system for system sizing and reliability. In the past few years, a new trend has been observed in growth of meta-heuristic and

artificial intelligence based optimization algorithms. Few more techniques such as bacterial foraging algorithm [Bazyar *et al.* (2011)], harmony search [Maleki and Askarzadeh (2014)], game theory [Khare *et al.* (2012)], tabu search [Maleki and Askarzadeh (2014)], improved bat algorithm [Bahmani-Firouzi and Aziziipannah-Abarghooee (2014)], gravitational search algorithm [Wu *et al.* (2015)], imperialist competitive algorithm [Gharavi *et al.* (2015)] and cuckoo search [Sanajaoba and Fernandez (2016)] have been applied in the current literature. These above discussed techniques have some major disadvantages and advantages. In some complex optimization problem, many of the algorithms fail to find out the optimal solution.

## 1.6 Hybrid techniques

Most of the evolutionary computational techniques faces drawback of premature convergence. These techniques require long time to come out from the local maxima or minima [Khare and Rangnekar (2013)]. By exploiting the advantages of two or more than two optimization techniques, hybrid techniques can be applied to various optimization problems. In the past few years, the research on hybrid technique has drawn more attention. Hybrid techniques are more powerful and competitive as compared to individual methods. In recent years, various authors have applied hybrid techniques in standalone solar, wind and solar-wind hybrid systems. Kalogirou (2004) and Mellit *et al.* (2010) applied neural network and GA for sizing of photovoltaic systems.

Khatib *et al.* (2012) proposed a case study in Malaysia to deduce optimal number of components of the hybrid system. The number of PV panels, wind turbines and batteries were the main decision factors. The authors implemented a combination of iterative and GA method. A set of possible configuration was found by iterative method and GA was used for optimum configuration. Askarzadeh (2013) proposed a hybrid technique by integrating three well-known algorithms, namely, chaotic search (CS), HS and SA to obtain sizing of a PV-wind based system. By merging all three techniques, the author created a discrete chaotic harmony search-based simulated annealing algorithm, named DCHSSA. The superiority of the proposed algorithm has been identified over individual technique. Xu *et al.* (2005) proposed optimal size of the components of a standalone hybrid wind-PV power system, by using mixed multiple-criteria integer programming problem. The GA was proposed to minimize the total capital cost

subjected to the constraint of the LPSP. [Katsigiannis \*et al.\* \(2012\)](#) proposed a hybrid TS-SA optimization technique by exploring the importance of individual algorithm. It is evident from the results that the hybrid technique provides a quality solution within less computational time. Recently, [Ahmadi and Abdi \(2016\)](#) presented a hybrid big bang-big crunch algorithm to design an optimal hybrid solar, wind and battery system. [Maleki \*et al.\* \(2016\)](#) presented a PSO based monte-carlo simulation (PSOMCS) for unit sizing of off-grid hybrid system consisting of solar, wind and batteries.

## 1.7 Multi-objective optimization

When designing with several objectives simultaneously, some of the objectives are conflicting and complicated with different priority. Multi-objective evolutionary algorithm (MOEA) generates multiple feasible solutions and tradeoff between them for a single solution, best suitable for the objectives of the problem [[Baños \*et al.\* \(2011\)](#)]. The main objective considered in major studies was the total NPC of the system for a lifespan. The others major objectives considered are pollutant emissions ( $CO_2$ ) and unmet load. MOEA is becoming popular in current years for multi-objective optimization problems. After 2006, Bernal and Dufor-Lopez and their research team started using multi-objective problems in hybrid systems. Later they developed a computer program called HOGA to design a stand-alone system. Initially, multi-objective problem was to minimize NPC and pollutant emissions by using strength pareto evolutionary algorithm (SPEA), particularly for PV-wind based system. Later the authors introduced a third objective, i.e. unmet load in the hybrid system optimization problem [Dufo-lópez \*et al.\* \(2011\)](#). For three objectives, problems become very complex, so conventional and non-conventional techniques fail to solve in reasonable computational time.

It is inferred from the literature that most popular software tool HOMER minimizes mainly single objective, i.e. NPC of the system, however, some sensitivity analysis can be performed. Moreover, MOEA has the advantage of minimizing simultaneously more than one objective. [Bilal \*et al.\* \(2010\)](#) applied a multi-objective genetic algorithm (MOGA) on hybrid PV-wind battery system based on ASC and LPSP for an isolated site in Senegal. Later on, [Bilal \*et al.\* \(2013\)](#) proposed MOGA approach to find component size of a hybrid PV-wind-diesel with storage. Two main parameters such as LCOE and  $CO_2$  emissions were minimized

simultaneously. The system total cost and pollutant emissions were also minimized by applying a NSGA-II multi-objective algorithm in a hybrid system by [Katsigiannis \*et al.\* \(2010\)](#). [Abbes \*et al.\* \(2014\)](#) considered three multi-objectives, i.e. embodied energy, life cycle cost and LPSP to design a hybrid standalone system.

[Shi \*et al.\* \(2007\)](#) proposed MOGA and NSGA-II to optimize the components of PV-wind hybrid power system. A robust system was designed while considering three main factors, NPC, LCOE and system autonomy. [Perera \*et al.\* \(2013\)](#) simultaneously minimized LCOE, wasted renewable energy, unmet load and fuel for an autonomous hybrid system. The authors implemented a combination of Fuzzy-TOPSIS with pareto multi-objective optimization. [Agarwal \*et al.\* \(2013\)](#) presented a multi-objective optimization model to deduce sizing of small PV-diesel-battery based hybrid energy system for un-electrified remote village in India. The authors minimized two main objective i.e., life cycle cost and  $CO_2$  emissions. [Zhao \*et al.\* \(2014\)](#) used GA-based method to solve the optimization sizing problem with multi-objectives for Dongfushan micro-grid project in China. Two factors, i.e. Life-cycle cost and pollutant emissions were minimized while maximizing the penetration of renewable energy source. [Sharafi and ELMekkawy \(2014\)](#) proposed a PSO based approach to handle simultaneously three objectives such as total NPC, unmet load and fuel emission. A detail review on multi objective algorithm problems in renewable based hybrid system have been presented by [Fadaee and Radzi \(2012\)](#) and [Bourennani \*et al.\* \(2014\)](#). Recently, a multi-objective optimization is performed by [Dufo-López \*et al.\* \(2016\)](#) to minimize total NPC of the hybrid system while human development index and job creation were maximized.

It can be inferred from these studies that limited literature was found in the multi-objective problem for renewable based systems. The real time engineering problems required more attention while considering competing and contradicting objectives. Based upon detailed discussion and analysis, above [Table 1.4](#) summarizes the advantages and disadvantages of different optimization techniques for better understating. Based upon the literature published in the last 10 years the percentage sharing of optimization techniques is presented in [Figure 1.6](#). It is also evident that a new trend is seen in utilization of new generation evolutionary algorithms for sizing and management of hybrid energy systems [[Sinha and Chandel \(2015\)](#)]. It is observed that the evolutionary algorithm share maximum percentage, while hybrid techniques share least. The software tools are also widely applied to optimize hybrid systems. An opti-

Table 1.4: Advantages and disadvantages of the optimization techniques

Method	Advantages	Disadvantages
Software tools	<ul style="list-style-type: none"> <li>• Easy to use, simple and straight-forward</li> <li>• Freely and commercially available</li> <li>• Professional training not required</li> </ul>	<ul style="list-style-type: none"> <li>• Black box approach</li> <li>• Algorithm and calculations are not visible</li> <li>• Simulate one configuration at one time</li> </ul>
Conventional technique	<ul style="list-style-type: none"> <li>• Easy to write code</li> <li>• Easy to understand</li> <li>• Simple and vast applications</li> </ul>	<ul style="list-style-type: none"> <li>• Constraints handling is not satisfactory, computational time more</li> <li>• Don't provide a global optimal solution, Often trap in local maxima or minima</li> </ul>
Non-conventional techniques	<ul style="list-style-type: none"> <li>• Less computational time</li> <li>• Attain global optimum with relatively computational</li> <li>• Simplicity and vast application</li> <li>• Easily available in literature</li> <li>• Suitable for a number of parameters</li> <li>• More efficient, Better ability to handle constraints</li> </ul>	<ul style="list-style-type: none"> <li>• Training procedure required</li> <li>• Not easy to code</li> <li>• complex structure</li> <li>• for more number of parameter response time increase</li> <li>• Solution clumps together in similar group</li> <li>• Long time to come out from local optima, sometime premature convergence</li> </ul>
Hybrid techniques	<ul style="list-style-type: none"> <li>• Better convergence</li> <li>• More competitive as single technique</li> </ul>	<ul style="list-style-type: none"> <li>• Hard to analyze, complex in nature</li> <li>• Less literature available</li> </ul>
Multi-objective evolutionary algorithm	<ul style="list-style-type: none"> <li>• Can optimized simultaneously more than one objective</li> <li>• Fast and growing in engineering applications</li> </ul>	<ul style="list-style-type: none"> <li>• Complex problem as compared to single objective</li> <li>• Hard to analyze as objective are conflicting in nature</li> </ul>

mally designed hybrid system must be cost effective and should have intelligent power management. The next section presents an overview of power management and control of hybrid wind-solar system.

## 1.8 Power management and control of hybrid systems

The biggest challenges with any renewable based hybrid energy system are proper management and coordination control to assure interrupted power supply to the consumer. Intermittent nature of solar and wind resources lead to disturbance in stability, irregularity and quality of power [Nema *et al.* (2009)]. Zhou *et al.* (2007) proposed a control strategy of hybrid system consisting wind farms and solar power in grid connected and islanded mode. The reactive and active power have been controlled using voltage source inverters. Numerous conventional and intelligent approaches have been applied for coordination, control and power management of hybrid systems. Chedid and Rahman (1997) designed a controller that continuously monitors

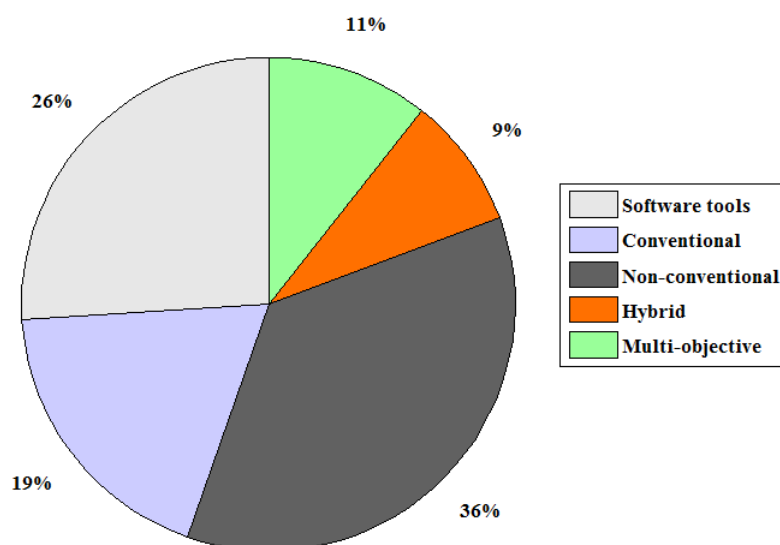


Figure 1.6: Percentage sharing of optimization techniques in literature in last 10 years

the operation of autonomous and grid connected hybrid system. The proposed controller keeps track of energy available at the various components and manage an optimized power management between the components of the hybrid system. Chedid *et al.* (1998) investigated a decision support technique to help designer to observe the influencing factors for grid-integrated hybrid solar-wind power systems. Valenciaga *et al.* (2003) designed a controller to control the power flow of a PV-wind hybrid system. Later on, Valenciaga and Puleston (2005) proposed three modes of controller by using the sliding mode control method.

Wang and Nehrir (2008) discuss power management strategy for the system to coordinate the power flow between wind-PV-Fuel cells based hybrid system. System performance

was verified by using simulation under different scenarios using practical load profiles and real weather data. [Shengtie and Zhiyuan \(2009\)](#) analyzed the energy flow and operational characteristic of a standalone wind-PV system for reliable operation. [Ribeiro \*et al.\* \(2011\)](#) proposed a Micro-grid incorporating PV and wind as energy sources for a small island in Brazil. The uninterrupted power supply was maintained for the user with the help of smart power center. [Liu \*et al.\* \(2011\)](#) designed a hybrid AC-DC micro-grid based on wind-PV systems. Coordination schemes were proposed to harness maximum power from wind-PV system. [Hong and Chen \(2014\)](#) designed an intelligent controller for grid integrated hybrid PV-wind power system. [Aissou \*et al.\* \(2015\)](#) proposed power control in a hybrid solar, wind and battery system with the help of LabVIEW software.

## 1.9 Scope of the study

### 1.9.1 Motivation

A huge part of the world's total population lives in developing countries. In developing countries power crisis is a major issue and mostly part of population are remotely located. The Utilization of RESs has become increasingly significant, attractive and environmentally friendly option to provide electricity demand of such areas. RESs are gradually entering into the mainstream of power generation. In a particular geographical location, different types of natural energy resources may be available for electricity option. By harnessing these locally available options electricity demand can be met in a reliable manner. Moreover, integrated renewable energy system along with storage system may be a feasible solution for power generation in such areas.

In recent years, solar and wind energy systems are gaining popularity due to their availability and geographical advantages as distributed energy resources. However, intermittent nature and dependency on weather and climatic changes of both the solar and wind sources are major concerns in designing of solar and wind based energy systems. Neither, a stand-alone solar or wind energy system can provide a continuous power supply to area with out any back-up or storage. Fortunately, the issues caused by the indeterminacy can be reduce by integration of more than one energy resources in a proper combination. In addition, of solar and wind other renewable sources such as biomass and FCs can also be integrated in the hybrid system.

Further, integration of hybrid energy systems with the utility grid is also a challenging job.

Mathematical modeling of the different components used in proposed systems is major design issue. It is observed that in the last few years, various optimization methods and software tools have been evolved to design an optimal hybrid energy system. Components sizing and power management become a critical issue for cost analysis and reliability of the systems. Most of the studies on hybrid systems containing solar, wind and biomass are carried out software tools. In this work, applicability of meta-heuristic algorithms have been explored in renewable based energy hybrid systems. This work intends to provide a better perspective of mathematical modeling of the system with operational strategy. For the power management, a novel droop based controller is proposed to control power flow between the different components of a hybrid system.

### **1.9.2 Objectives of the research work**

The main objective of this thesis is to analyze different configurations of the hybrid renewable based energy systems in terms of cost of energy and reliability. The main objective in designing of a hybrid system is proper selection of components while minimizing the total NPC of the project. Proper selection of components leads to a reliable system. The designed system must be optimal in terms of cost and reliability. The biggest challenges with any renewable based hybrid energy system are proper management and coordination control to assure interrupted power supply to the consumer. Intermittent nature of renewable energy sources lead to disturbance in stability, irregularity and quality of power. Detailed mathematical modeled have been developed and a simplified operational strategy is presented for all configurations. The main objectives of this research work are summarized as follows:

1. To formulate an objective function for hybrid system consisting unmet load and environmental impacts.
2. To determine the optimum number of solar panels, wind turbines, batteries, etc for given power generation/load and for a given site.
3. To analyze different techno and economic aspects over the cost of energy from the different options available.
4. To develop a strategy for automatic power selector in case of multiple options of energy.

### 1.9.3 Contribution

This work intend to provide a detail mathematical modeling of different configurations of the hybrid system. Optimal component sizing of the components leads to a reliable and economic system. In this work, three different hybrid configurations, i.e., solar-wind with battery, solar-wind-battery-biomass and solar-biomass grid integrated have been proposed. The cost analysis is performed by using meta-heuristic algorithms and software tool. A brief comparison of results have been performed. Some critical issues such as failure of one unit and sensitivity analysis also have been carried out. At last, a power management in a hybrid system is performed by altering the charging and discharging rates of battery bank. A novel droop based controller is proposed for smooth functioning of the hybrid system.

## 1.10 Organization of the thesis

This thesis has been divided into six chapters. Chapters 2, 3 and 4 deals with cost analysis of different configurations of the hybrid systems. These chapters emphasizes on the optimal selection of components of the systems to get desired reliability and NPC. Chapter 5 deals with the optimal power management into hybrid systems. A conclusion of the work is given in chapter 6. In the next five chapters, brief overview of the work done is presented in detail.

1. In chapter 2, a hybrid system consists of solar PV panels, wind turbines with battery storage have been modeled. The resource data such as solar radiation, wind speed and component costs have been collected. In order to evaluate the levelized cost of energy a meta-heuristic algorithm i.e. ABC has been applied. A brief introduction of algorithm is presented with detail operational steps. The results obtained from proposed techniques have been compared with other technique and software tool HOMER for reference.
2. In Chapter 3, a hybrid system consists of wind, PV and biomass with battery storage is proposed to satisfy the energy needs of the a small area. The testing and validation of the model outputs is performed with the help of three optimization technique i.e., ABC, PSO and HOMER. A brief comparison of the results obtained by the various method is presented. Performance and reliability of the proposed system in the critical cases such as failure of any generating unit has been observed.

3. Chapter 4 presents an optimal sizing methodology for a stand-alone and grid connected PV-biomass hybrid energy system. Further, ABC algorithm is applied to obtain the optimum hybrid system configuration with the least LCOE while minimizing ASC. It has been observed from the results that a grid connected hybrid PV-biomass system is cost effective and reliable choice for rural electrification as compared to stand-alone hybrid PV-biomass energy system. A brief comparison of results obtained from the ABC algorithm and HOMER has been carried out. Moreover, it is also observed from the results that the ABC algorithm provides better results as compared to HOMER.
4. Chapter 5 mainly emphasizes on optimal power management of a hybrid energy system consisting of RESs and distributed energy storage system. A droop based controller is proposed for optimal power management of batteries. An aggregator has been suggested at the micro-grid (MG) which distributes the power among the various charging stations (CSs) and each CS finally distributes the power among the individual batteries based on droop participation factor. Moreover, the charging and discharging rates of batteries are controlled to achieve the desired power flow between the MG and CSs.
5. Chapter 6 presents brief summary and conclusions of all the chapters and the recommendation for further research.

## Chapter 2

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# HYBRID SOLAR-WIND WITH BATTERY SYSTEM

---

### 2.1 Introduction

In the last few years, renewable based hybrid energy system has found attention due to increasing environmental concerns, energy demand, fuel prices and depletion of fossil fuels. In particular, solar and wind based generation systems have become sustainable and environmentally friendly options to supply power in isolated or off grid locations. Solar PV energy conversion systems along with storage system have proved to be a very attractive method to provide electricity to the places like remote or off grid locations, residential households, off-grid location and commercial buildings. However, PV generation has a low energy conversion efficiency and cost of electricity per  $kWh$  is high. This led to a substantial growth in wind based power generation. However, the major drawbacks for both wind and solar energy sources are their stochastic nature which raises concern about the reliability of power to the user. Therefore, to enhance the reliability, hybridization of both wind and solar energy is a suitable alternative. One's weakness can be compensated by the strengths of another. However, it increases the complexity of the system. Stand alone solar-wind based hybrid energy systems have been analyzed in various researches in terms of cost effectiveness. Multi-generation or hybrid systems results in higher efficiency and reduction of pollution emissions [[Chicco and Mancarella \(2006\)](#)].

In this chapter, a hybrid energy system consisting of PV-wind with battery storage for a typical electrical demand is investigated in terms of its cost effectiveness. The work has been validated by using a recently introduced swarm based ABC algorithm for optimal combination and sizing of components while ensuring the continuous meeting of the electricity demand. In parliamentary law to verify the strength of the proposed algorithm, the results received from

the ABC algorithm have been compared with the results obtained from the standard software tool HOMER and PSO algorithm.

The main intend of this work is to explore applicability of ABC in the renewable based hybrid system. ABC algorithm simulates the foraging behavior of honey bee colonies [Basturk and Karaboga (2006)]. This algorithm has been recently used to resolve real-parameter, nonlinear, multi-modal, and numerous other problems and its execution were found acceptable. The major factor which differentiates ABC algorithm from other algorithms (such as GA and PSO) is that it employs less number of control parameters. In a standard GA there are three control parameters (crossover rate, mutation rate, generation gap). A simple PSO has three control parameters (inertia weight, cognitive and societal factors). The other two common parameters are the maximum evaluation number and population size. In ABC algorithm, apart from maximum evaluation number and colony size, there is merely a single control parameter named 'limit'. Hence, it is easy to adjust the single control parameter. The other element which differentiates ABC from PSO and GA is in its search process. In case of GA and PSO, the best result achieved in each generation is forever held in the population and further it can be utilized to create new population (in the case of GA) and new velocities (in the case of PSO). Nevertheless, in ABC, the best solution achieved is not held in the population, only a randomly produced solution by the scout is entered. This feature provides the ABC algorithm a better global search ability and power to come out from premature convergence [Karaboga and Basturk (2008), Karaboga *et al.* (2014)].

ABC has found applications in other engineering optimization problems and applied by various researchers in other areas like strategic bidding in transmission market [Jain *et al.* (2012)], economic load dispatch problem [Hemamalini and Simon (2010)], thermal unit commitment problem [Chandrasekaran *et al.* (2012)], optimal placement of capacitors in radial network [El-Fergany and Abdelaziz (2014)], stand-alone PV system [Mohamed *et al.* (2014)], optimal power flow in wind farms [Raj *et al.* (2014)], energy consumption prediction [Gürbüz *et al.* (2013)], optimal management of micro-grid [Govardhan and Roy (2012)] and many more. ABC proved to be simple to use, flexible and robust optimization algorithm. The ABC algorithm has been used to find out optimal configurations of a stand-alone hybrid wind-solar with battery system to fulfill the electrical demand of a village located near Patiala, Punjab, India. To verify effectiveness of the proposed system, the results obtained by the ABC algo-

rithm are compared with PSO and HOMER. A brief comparison is performed on the basis of LCOE for all configurations obtained by different methods. The configuration with least COE is considered the optimal one. In next section, a mathematical modeling of components used in the hybrid system is discussed in detail.

## 2.2 Mathematical model of hybrid system

The proposed hybrid renewable generation system in this study consist of different components such as wind turbine (WT), solar PV panel, storage batteries and converter. Figure 2.1 shows the different components of the proposed hybrid renewable energy system. The methodology for modeling for different components of a hybrid renewable generation system are discussed as follows

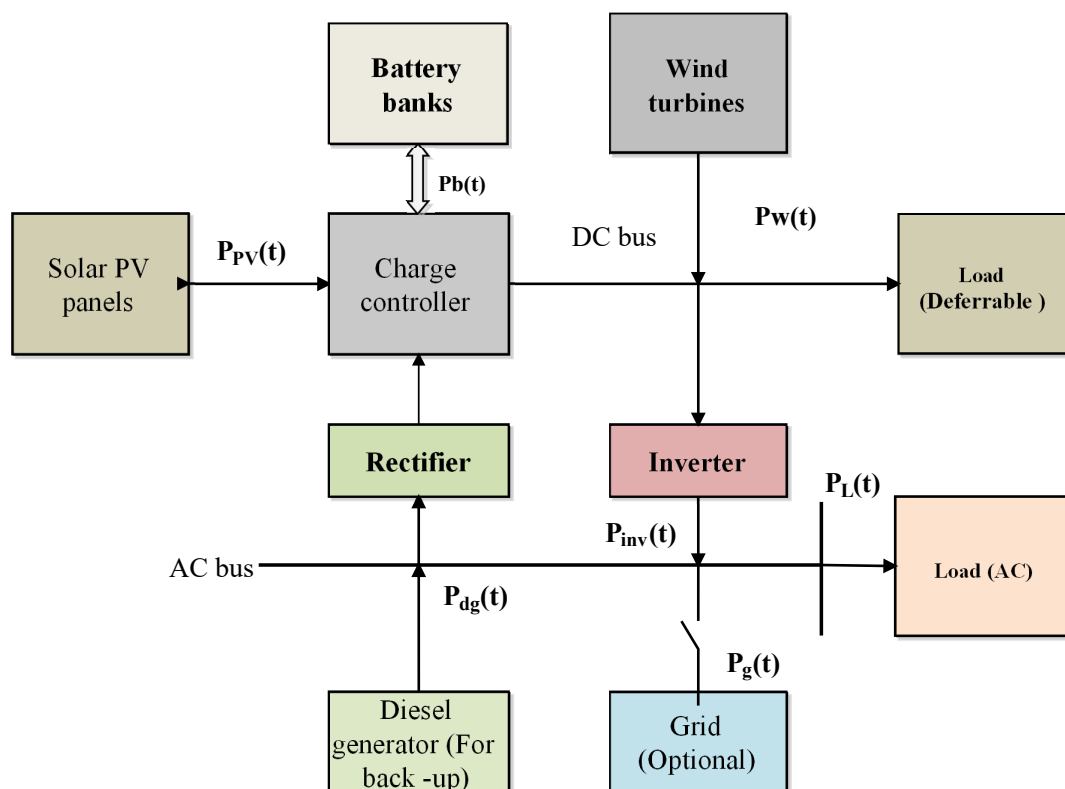


Figure 2.1: Different components of the proposed system

### 2.2.1 Solar photovoltaic panel

The output of a solar PV panel depends mainly upon atmospheric conditions and geographical locations. The output power of a particular solar PV panel, ( $P_{sol}$ ), at any time is a function of solar radiation and atmospheric conditions and it is expressed as,

$$P_{sol}(t) = P_{rat} f_{loss} \frac{G_h(t)}{G_S} [1 + \alpha_P (T_c - T_s)] \quad (2.1)$$

where,  $P_{rat}$  is the rated power output capacity of the solar PV panel,  $f_{loss}$  is the loss factor of solar PV panel due to dirt, shadow, temp etc,  $G_h(t)$  is the hourly solar radiation incident on the solar PV panel ( $W/m^2$ ),  $G_S$  is the standard incident radiation ( $1000W/m^2$ ),  $\alpha_p$  is the temperature coefficient of power,  $T_c$  is the PV cell temperature in the current time step and  $T_s$  is the PV cell temperature under standard test conditions [Xu *et al.* (2013), HOMER (2016)].

While considering changes in cell performance with temperature, manufacturers often provide an indicator called the NOCT (Nominal operating cell temperature). The NOCT is cell temperature in a module when ambient temperature is  $20^\circ\text{C}$ , solar irradiation is  $0.80 \text{ kW}/m^2$ , and windspeed is  $1 \text{ m}/s$ . To account for other ambient conditions, the following expression may be used

$$T_c(t) = T_{amb} + \frac{NOCT - 20^\circ}{0.8} G_S \quad (2.2)$$

where,  $T_{amb}$  is the ambient temperature.

In this study, the effect of temperature on the PV array has not been taken into consideration. By assuming the temperature coefficient of power to zero Eq. (2.1) can be written as

$$P_{sol}(t) = P_{rat} f_{loss} \frac{G_h(t)}{G_S} \quad (2.3)$$

### 2.2.2 Wind power generation

The power generated by a wind turbine ( $P_{wt}$ ) can be calculated as,

$$P_{wt}(t) = \begin{cases} 0 & V(t) \leq V_C \text{ or } V(t) \geq V_F \\ P_r^w & V_R \leq V(t) \leq V_F \\ P_r^w \frac{V(t)-V_C}{V_R-V_C} & V_C \leq V(t) \leq V_R \end{cases} \quad (2.4)$$

where,  $P_r^w$  is the rating of a single wind turbine,  $V_C$  is the cut in speed,  $V_R$  is the rated wind speed,  $V_F$  is the furlong speed and  $V(t)$  is the wind speed at desired height [Yang *et al.* (2007), Li *et al.* (2016)]. The wind speed distribution is a site specific parameter and at a different hub heights the wind speed is different. A output of a wind turbine may be varying with the hub height due to variation of wind speed. The wind speed at the hub height depends upon site and geographical location and it is different from reference height, further, it is expressed as,

$$V = V_r \left( \frac{H_{WT}}{H_r} \right)^\gamma \quad (2.5)$$

where,  $V$  is the wind speed at height ( $H_{WT}$ ),  $V_r$  is the wind speed at reference height  $H_r$ , and  $\gamma$  is friction coefficient. Typical value of friction coefficient  $\gamma$  is 1/7 for low roughness, surface and well exposed site [Salameh and Safari (1992), Olaofe and Folly (2013)].

The major technical information of a wind turbine is specified by power curve. Power curves represents how their wind turbine output varies with wind speed. The power curve of a wind turbine is nonlinear and data is provided by the manufacturer.

Figure 2.2 show idealized curve of a typical wind turbine. No wind power is generated below  $V_C$ . Between  $V_R$  and  $V_F$  the output power of wind turbine is equal to the rated power. Above  $V_F$  no power is generated [Masters (2004)].

### 2.2.3 Battery bank

Batteries are used in hybrid renewable energy system to store excess energy and to operate when power from renewable systems is insufficient or absent. The measurement of energy can be achieved with the proper estimation of the state of charge (SOC). The SOC of the battery is

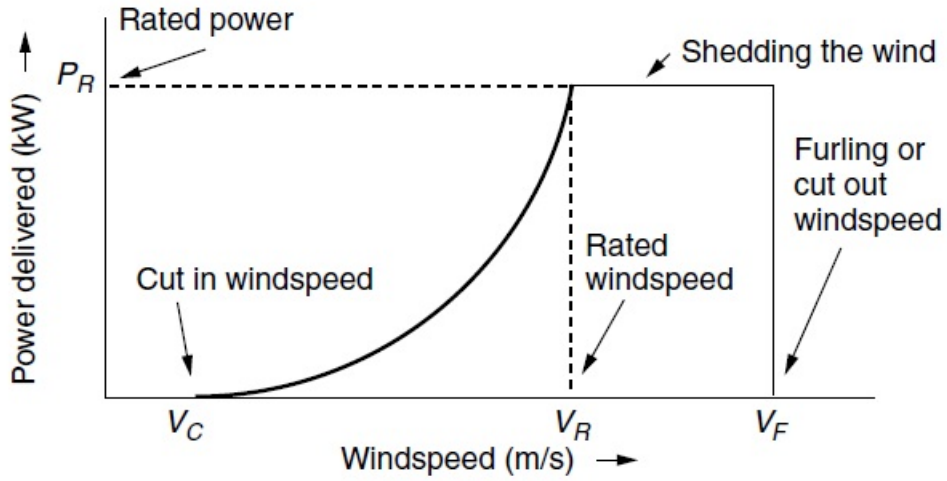


Figure 2.2: A typical wind turbine characteristic [Masters (2004)]

a function of time and it can be calculated as,

$$SOC(t) = SOC(t - 1) + \Delta t [P_b(t) \eta_{batt} / V_{bus}] \quad (2.6)$$

where,  $V_{bus}$  is the voltage of bus,  $\Delta t$  is time interval,  $P_b(t)$  is battery's input/output power and  $\eta_{batt}$  is the round trip efficiency of the battery. If  $P_b(t)$  is positive, battery is charging else it is discharging. It is assumed that during charging and discharging, efficiencies are different and considered to be 85% and 100% respectively [Zhou *et al.* (2008)].  $SOC_{max}$  is the maximum value of SOC and is equal to the aggregate capacity of the battery bank ( $C_n(Ah)$ ) and it is given as follows,

$$C_n(Ah) = \frac{N_{batt}}{N_{batt}^s} C_b(Ah) \quad (2.7)$$

where,  $C_b(Ah)$  is the single battery capacity,  $N_{batt}$  is the total number of batteries,  $N_{batt}^s$  is the number of batteries connected in series [Belfkira *et al.* (2011)].

The battery bank can not discharge beyond a minimum limit which is called  $SOC_{min}$ . This limit can be used as system constraints according to the usage of battery bank. This limit is called depth of discharge (DOD, in %) and it is a measure of maximum permissible discharge from the battery [Diaf *et al.* (2008), Upadhyay and Sharma (2015)]. If the maximum value of

SOC is 1, then minimum SOC of the battery can be calculated as,

$$SOC_{min} = 1 - DOD \quad (2.8)$$

DOD, is a indicator to show how deeply the battery is discharged. DOD always can be treated as how much energy that the battery delivered. For a example, if a battery is 100% fully charged, it means the DOD of this battery is 0%, If the battery have delivered 30% of its energy, here are 70% energy reserved, the DOD of this battery is 30%. And if a battery is 100% empty, the DOD of this battery is 100%. If battery's DOD is exceeded frequently, the battery can suffer from over-discharge, and prolonged over-discharge which may result in permanent damage of the battery.

To obtain desired bus voltage, batteries are connected in series. The number of batteries connected in series can be calculated as,

$$N_{batt}^s = \frac{V_{bus}}{V_{batt}} \quad (2.9)$$

where,  $V_{batt}$  is the voltage of a single battery .

Another major factor in battery modeling is the maximum charge or discharge power at any time. It depends upon maximum charge current, and can be calculated by the following equation,

$$P_b^{max} = \frac{N_{batt} V_{batt} I_{max}}{1000} \quad (2.10)$$

where,  $I_{max}$  is the battery's maximum charging current in amperes.

## 2.2.4 Diesel generator

In this case study, a rated diesel generator is considered for back-up and it is running at rated capacity for maximum efficiency. The rate of hourly fuel (diesel) consumption is a major design constraint and is defined as follows

$$q_1(t) = k_1(P_{dg}) + k_2(P_{dg}(t)) \quad (2.11)$$

where  $P_{dg}$  (kW) is the rated power of the diesel generator,  $P_{dg}(t)$  (kW) is the power generated at any instant,  $k_1$  (l/kWh) and  $k_2$  (l/kWh) are the fuel curve coefficients provided by the manufacturer [Skarstein, O., Ulhen (1989), Upadhyay and Sharma (2015)].

The usage of diesel generator emits carbon dioxide ( $CO_2$ ) as greenhouse gas. The amount of  $CO_2$  emitted per liter of the fuel used depends upon the carbon content of fuel burn. For example, burning of diesel emits of 2.4 to 2.8 kg/l of  $CO_2$ . Further, the diesel generator can be operated in two modes (i) First in load following strategy, i.e. whenever it operates, it generates only required power to meet the primary load demand. (ii) In second strategy, it operates at rated capacity or minimum load ratio. In case diesel generator is operating at rated capacity, the surplus power fed to charge the batteries.

### 2.2.5 Power converter

DC/AC and AC/DC power converters are required when there are AC and DC components in the system. Solar PV panels and batteries are generating DC output while load considered is AC. The converter size is opted based upon peak load demand [ $P_L^m(t)$ ]. The inverter rating  $P_{inv}$  is calculated as follows,

$$P_{inv}(t) = P_L^m(t)/\eta_{inv} \quad (2.12)$$

where,  $\eta_{inv}$  denotes efficiency of the inverter.

## 2.3 Problem formulation and algorithm

### 2.3.1 Objective function

The objective function considered in this case study is the total system cost, which consists of (i) total capital cost (ii) replacement cost and (iii) operational & maintenance cost. Installation and other costs are included in the capital cost. In this work, concept of annualized cost of the system has been used [Yang *et al.* (2008)]. The system with lowest ASC is considered optimal one while satisfying other constraints. The objective function which need to be minimized is expressed as follows

$$\min(ASC) = [N_{sol}C_{sol} + N_{wind}C_{wind} + N_{batt}C_{batt} + P_{inv}C_{inv} + C_{dg}] \quad (2.13)$$

where  $C_{sol}$ ,  $C_{wind}$ ,  $C_{batt}$ ,  $C_{inv}$ ,  $C_{dg}$  are the annualized cost of each solar PV panel, wind turbine, battery, inverter and diesel generator respectively. The objective function is minimized, subject to the constraints defined in the next section. The annualized cost of any component is further composed of three components as mentioned below.

### Annualized capital cost

The capital cost of the component includes the cost of installing and purchasing of components. The annualized capital cost of each component can be calculated by using capacity recovery factor (CRF). For example, in case of solar panel it can be calculated as,

$$C_{acap}^{sol} = C_{cap}^{sol} CRF(r, n) \quad (2.14)$$

where,  $C_{cap}^{sol}$  is the initial capital cost of the solar panel and CRF is a capital recovery factor. CRF is a factor to calculate present value of money. For a lifetime of  $n$  years and interest rate  $r$ , CRF can be calculated as,

$$CRF(r, n) = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (2.15)$$

### Annualized replacement cost

The annualized replacement cost of the solar panel is the cost of replacing at the end of life of the solar panel. The annualized value of total replacement cost,  $C_{arep}^{sol}$ , which occurred during the lifetime of a project life can be given as,

$$C_{arep}^{sol} = C_{rep}^{sol} CRF(r, n) \frac{1}{(1+r)^y} \quad (2.16)$$

where,  $C_{rep}^{sol}$  is the replacement cost of the component and  $y$  is the lifetime of the solar panel in years. The replacements are required if the lifetime of the project ( $n$ ) is greater than component lifetime ( $y$ ).

### Salvage value

It is defined as the value remaining of a component at the end of project life. The salvage value of the solar panel can be calculated as,

$$C_{sal}^{sol} = C_{rep}^{sol} \frac{R_{rem}}{N_{sol,l}} \quad (2.17)$$

where,  $C_{rep}^{sol}$  is the replacement cost of the component,  $R_{rem}$  is the remaining life of the solar panel and  $N_{sol,l}$  is the life span of the solar panel.

The major economic parameter which defines cost effectiveness of the proposed hybrid energy system is levelized cost of electricity. The levelized cost of electricity is defined as the average cost per  $kWh$  of the effective electricity produced by the system and it can be expressed as,

$$LCOE = \frac{ASC(\$/year)}{\text{Total electrical load served (kWh/yr)}} \quad (2.18)$$

### 2.3.2 Operational strategy and system constraints

To minimize the objective function, a certain number of constraints must be satisfied throughout the performance of the system. Due to the diverging nature of solar radiation and wind speed, the electricity generated by PV and wind turbines is time dependent. At any instant, the power produced by complete system should be equal to power demand.

### 2.3.3 Operational strategy

In case of any hybrid energy system, proper power management is required to achieve reliability of the system. In this system, diesel gasifier is kept on least priority, i.e. it is run when renewable and batteries are unable to meet the electricity demand. A simplified steps of operational strategy are as follows,

- If the total power generated by solar PV panels and wind turbines is sufficient, then demand can be served by renewable only. After satisfying the load, surplus power fed to

the battery bank and can be calculated as,

$$P_b(t) = P_{PV}(t) + P_w(t) - P_L(t)/\eta_{inv} \quad (2.19)$$

where,  $P_L(t)$  denotes load demand at any time and  $\eta_{inv}$  denotes the efficiency of the inverter. If  $P_{sol}(t)$  is the power generated by a individual solar PV panel and  $N_{sol}$  is the solar PV panels, then the total power generated by solar PV panels ( $P_{PV}(t)$ ) is given as,

$$P_{PV}(t) = P_{sol}(t)N_{sol} \quad (2.20)$$

Further, if  $P_{wt}$  is the power produced by a individual wind turbine and  $N_{wt}$  is the total wind turbines, then the total power generated by wind turbines ( $P_w(t)$ ) can be given as,

$$P_w(t) = P_{wt}(t)N_{wt} \quad (2.21)$$

- If  $P_b(t)$  is greater than the maximum allowable capacity of battery bank ( $P_b^{max}$ ) then excess energy could be dumped or can be given to deferrable loads. Excess or dump energy is obtained as,

$$P_{dump}(t) = P_b(t) - P_b^{max}(t) \quad (2.22)$$

- If solar PV panels and wind turbines are not generating adequate power, then balance power can be supplied by the battery and is calculated as,

$$P_b(t) = P_L(t)\eta_{inv} - \{P_{PV}(t) + P_w(t)\} \quad (2.23)$$

- If solar and wind power are inadequate and batteries  $\{SOC(t) \leq SOC_{min}\}$  are also not able to produce the desired power to meet the load demand, then diesel generator supply power to the load. Diesel generator can be operated in two ways,

1. In first strategy, whenever it operates, it generates only required power to meet the primary load demand. The power generated by the diesel generator is calculated as,

$$P_{dg}(t) = P_L(t) - \{P_w(t) + P_{PV}(t)\}/\eta_{inv} \quad (2.24)$$

2. In second strategy, it operates at rated capacity or minimum load ratio. In case diesel generator is operating at rated capacity, the surplus power is used to charge the batteries and further can be given as

$$P_b(t) = \{P_{dg}(t) - P_L(t)\} + \{P_w(t) + P_{PV}(t)\}\eta_{rec} \quad (2.25)$$

Further, the charging rates of the battery bank also be maintained within underspecified limit. The objective function is minimized enforcing a set of several constraints, which are summarized as

$$1 \leq N_{sol} \leq N_{sol}^m \quad (2.26)$$

$$1 \leq N_{wt} \leq N_{wt}^m \quad (2.27)$$

$$1 \leq N_{batt} \leq N_{batt}^m \quad (2.28)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (2.29)$$

where,  $N_{sol}^m$  is the maximum number of solar PV panels,  $N_{batt}^m$  is the maximum number of batteries,  $N_{wt}^m$  is the maximum number of wind turbines.

### 2.3.4 Artificial bee colony algorithm

An artificial bee colony consists three types of bees: employed, onlooker and scouts. Half of the colony bees are employed and the other half is onlooker bees. The number of food source is equal to the number of employed bees. After food source abandoned the employed bee becomes a scout. The search process of the bees can be summed up as follows,

- First employed bees find out a food source in the search area and remember the location of food sources in their memory.
- After that, employed bees share this information with onlookers bee which are basically waiting bees in the hive.
- Further, onlooker bee explore the food source based on information shared by the employed bees.
- After food source abandoned, the employed bee becomes a scout and start searching the

area randomly to find a new source [Karaboga and Basturk (2007), Karaboga and Akay (2009)].

The main steps of the implementation of the ABC algorithm to solve the optimization problem for the above mentioned hybrid system are described as follows,

1. The first step of optimization procedures is the input of annual data of the solar radiation and load demand. Initialize the control parameters of the ABC algorithm, i.e. max cycle number, colony size, population of food sources, dimension of the problem and limit.
2. Consider the number of food sources equals the half of the colony size. For this problem, the colony size is considered 20, so the initial solutions (food sources) are 10 (half of the colony size). The number of parameters to be optimized are 3 (numbers of solar PV panels, wind turbines and batteries).
3. Generate a randomly distributed population within the range of boundaries of the parameters (Eq. (2.26) to Eq. (2.28)) by using the following equation

$$P_{ij} = P_j^{min} + rand(0, 1)(P_j^{max} - P_j^{min}) \quad (2.30)$$

where,  $i = 1 \dots SN$ , here,  $SN$  denotes the size of the population and  $j = 1 \dots D$ , whereas,  $D$  is the dimension of the problem or number of optimization parameter.

4. Set trial counters (to store the number of solution trials) to zero.
5. According to initial guess solutions (number of solar PV panels, wind turbines and batteries) perform the following steps.
  - Obtain the solar PV panels and wind turbine output by using Eq. (2.20) and Eq. (2.21).
  - Obtain the annualized cost of sizing components by using Eq. (2.14) to Eq. (2.17) for initial population of food sources.
6. The objective function as described in Eq. (2.13) is evaluated for initial food source.
7. Cycle = 1.

8. **Repeat.**

9. Produced a new modified food location for the employed bees by using the following equation

$$P_{ij}^{new} = P_{ij} + \phi_{ij}(P_{ij} - P_{kj}) \quad (2.31)$$

where,  $k = 1, 2, 3 \dots SN$  is a randomly chosen index,  $j = 1, 2, 3 \dots D$  is randomly chosen index,  $k$  has to be different from  $j$ . Whereas,  $\phi_{ij}$  is the random integer between the range of  $[-1, 1]$ .

10. If a parameter generated exceeds its predetermined limits, it can be set to an acceptable boundary.

11. Evaluate the objective function described in Eq. (2.13) using new solutions by following the procedure mentioned in step 5.

12. Apply the greedy selection process for the employed bees.

13. Calculate the probability value,  $p_i$ , for the solutions using fitness value by following equation

$$p_i = \frac{fit_i}{\sum_0^{SN} fit_i} \quad (2.32)$$

where,  $fit_i$  is the fitness value corresponding to  $i^{th}$  solution.

14. Produce the new solutions  $P_{ij}^{new}$  by using Eq. (2.31) for the onlookers bees from the solutions selected depending upon the value of  $p_i$ .

15. Evaluate the objective function described in Eq. (2.13) using new solutions by following the procedure mentioned in step 5.

16. Apply the greedy selection process for the onlookers bees.

17. Determine the abandoned solution for the scout, if exists and replace it with a new randomly produced solution.

18. Memorize the best solution obtained as of now.

19. Cycle = Cycle + 1.

20. **Until** (Cycle = *Maxcycle*).

### 2.3.5 Particle swarm optimization

In 1995, Eberhart and Kennedy proposed a new stochastic optimization method based on social behavior of a flock of migrating birds or fish schooling. Each possible solution of any problem is termed as a particle in PSO. Each particle updates its position according to its own (local search) experience as well as the experience of other (global search) particles. When a flock of birds is flying they communicate each other, during flight each bird adjust its position and velocity. Each particle uses flying experience of others and his own flying experience in D-dimensional space. The local tracking of coordinates in problem space achieved so far is called pbest. Other values called as gbest is the best value achieved by any other neighbor particle of that particle. The PSO algorithm is motivated by changing the velocity of each particle toward its pbest and the gbest position at each time step [Kennedy and Eberhart (1995)].

Each particle tries to modify its current position and velocity according to the distance between its current position and pbest, and the distance between its current position and gbest. The updated velocity is given as:

$$v_i^{k+1} = wV_i^k + c_1r_1(pbest_i^k - x_i^k) + c_2r_2(gbest_i^k - x_i^k) \quad (2.33)$$

where,  $c_1$  and  $c_2$  are the cognitive and social components, respectively,  $r_1$  and  $r_2$  are random variables in the range of  $[0, 1]$ .  $x_i^k$  is the position of the particle at the  $k^{th}$  iteration and  $w$  is the inertia weight for velocity of the  $i^{th}$  particle [Khare *et al.* (2015)]. A suitable value of  $w$  provides better optimal solution. In each iteration, the weight  $w$  is varied as

$$w = w_{max} - \frac{w_{max} - w_{min}}{Iter} \quad (2.34)$$

The position of each particle is updated using the velocity vector as [Tan *et al.* (2013a)]

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (2.35)$$

## 2.4 Resource data

To demonstrate the efficacy of the algorithms, a case study has been introduced. A hybrid PV-wind with battery storage is proposed and analyzed in terms of cost effectiveness. The

system is designed to meet the load demand of the household of a very small village in India. The resource data, i.e. solar radiation, temperature and wind speed is taken from the NASA website. The electrical demand and other resource data are taken from [Mishra and Singh (2013)]. The system is designed for an average load: 16.1 kW, average (kWh/d): 387, load factor: 0.342 and with a peak load of 47.2 kW. Load considered in this study is AC only at a bus voltage of 120 V. Figure 2.3 shows electrical demand for both seasons, i.e., winter and summer for the case study. Figure 2.4 (a) and Figure 2.4 (b) shows yearly load demand and average monthly daily solar radiation on the site, respectively.

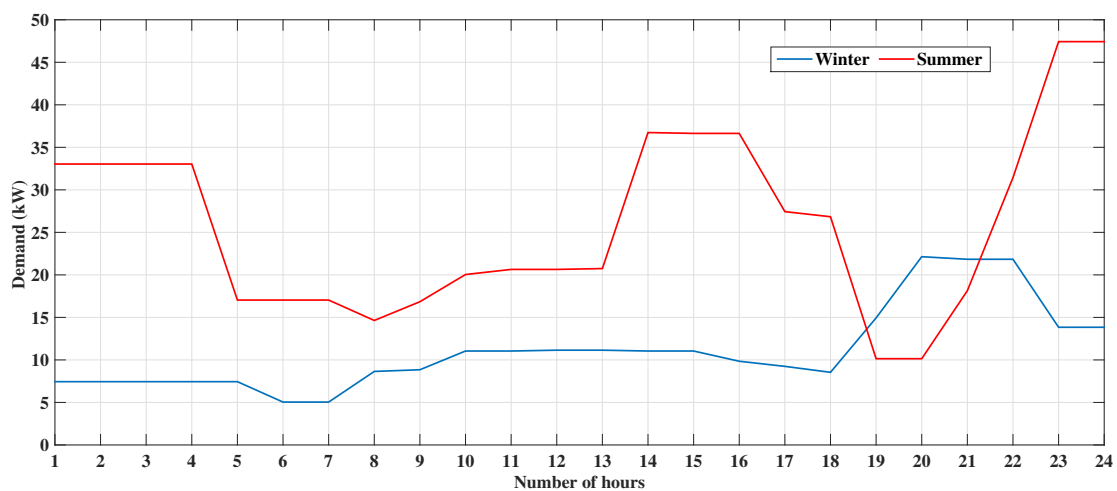


Figure 2.3: Load demand in winter and summer season

Figure 2.5 (a) and Figure 2.5 (b) demonstrates the wind speed data and wind speed histogram for the case study, respectively. Table 2.1 demonstrates economic and technical data for the components used in the study. The project life is considered to be 20 years while interest rate is considered to be 6%. The concept of the annualized cost of the system is most preferable economic method to deduce the LCOE of the system. LCOE is an average price of useful energy generated. The variables considered in the optimization are a number of solar panels, wind turbines and batteries. The battery state of charge is one major constraints considered in problem formulation. For longevity of life of the battery, the minimum SOC is maintained at 30%. Also, battery bank is the main components which required replacements during project lifetime.

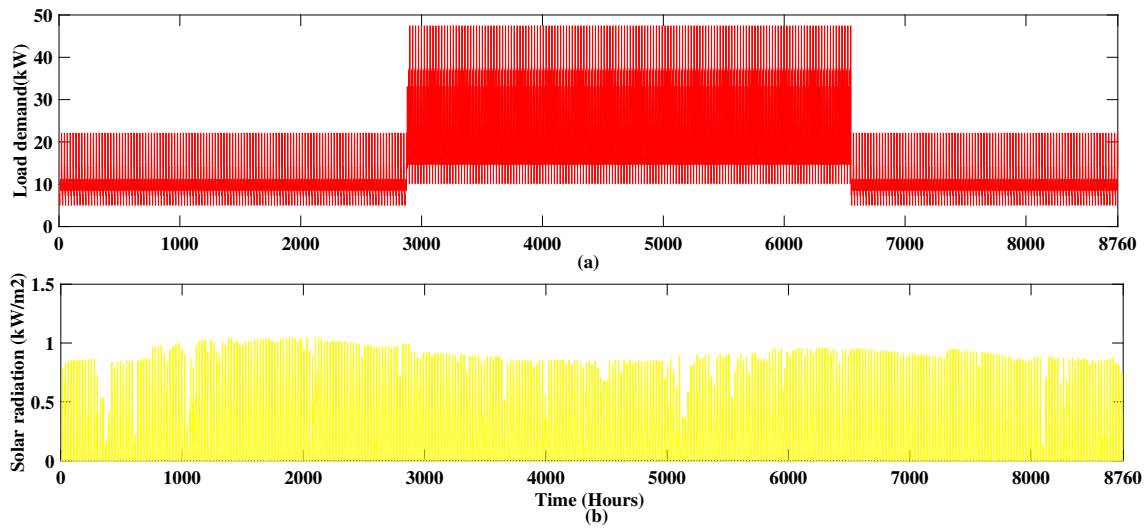


Figure 2.4: (a) Yearly load demand (b) Solar radiation data for one year

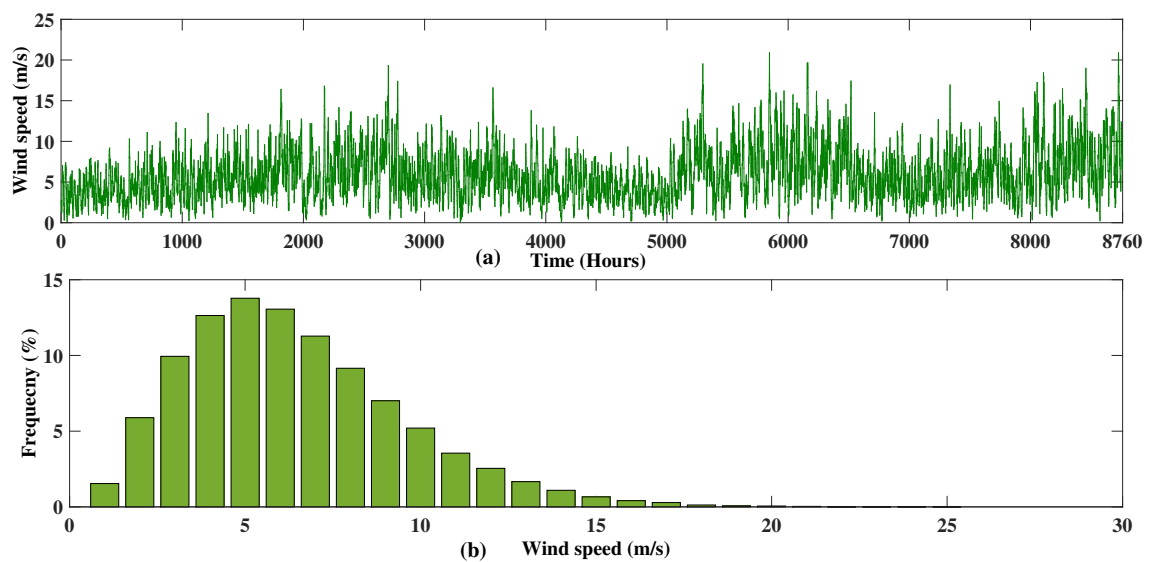


Figure 2.5: (a) Average wind speed data (b) Wind speed histogram

Table 2.1: Technical and economical data of the components used in proposed hybrid system

Component	Parameter	Value	Unit
<b>Wind turbine</b>	Rated power ( $P_r^w$ )	1	kW
	Cut in speed ( $V_C$ )	5	m/s
	Cut out speed ( $V_F$ )	20	m/s
	Capital cost	2,300	\$
	Replacement cost	1,500	\$
	O & M cost	2	\$/yr
	Hub height	50	m
	Life time	20	years
<b>Solar PV</b>	Rated power ( $P_r^s$ )	1	kW
	Derating factor ( $f_{loss}$ )	88	%
	Capital cost	1,200	\$
	Replacement cost	1,200	\$
	O & M cost	4	\$/yr
	Life time	20	years
<b>Battery</b>	Nominal capacity ( $C_b(Ah)$ )	360	Ah
	Nominal voltage ( $V_{batt}$ )	6	V
	Max charging rate	1	A/Ah
	Max charging current	18	A
	Minimum state of charge ( $SOC_{min}$ )	30	%
	Maximum state of charge ( $SOC_{max}$ )	100	%
	Round trip efficiency ( $\eta_{batt}$ )	85	%
	Capital cost	167	\$
	Replacement cost	67	\$
	O & M cost	1.67	\$/yr
Life time	5	years	
<b>Diesel generator</b>	Rated power	48	kW
	$k_1, k_2$	0.246, 0.0845	l/kWh
	Capital cost	278	\$/kW
	Replacement cost	278	\$/kW
	Fuel cost (diesel)	0.85	\$/yr
	Life time	15000	hours
<b>Converter</b>	Rated power	55	kW
	Round trip efficiency ( $\eta_{inv}$ )	85	%
	Capital cost	127	\$/kW
	Replacement cost	127	\$/kW
	O & M cost	1	\$/yr
	Life time	20	years
<b>System</b>	Interest rate ( $r$ )	6	%
	Project life ( $n$ )	20	years
	Bus voltage (DC) ( $V_{bus}$ )	120	V
	Batteries in string ( $N_{batt}^s$ )	20	units

## 2.5 Results and discussion

The proposed algorithm is performed by using MATLAB 2014a program. Proposed ABC and PSO algorithms have been applied to design a standalone hybrid PV/wind system with battery storages in order to meet the electricity demand of a hypothetical load as shown in [Figure 2.1](#). The load demand is met with the help of solar, wind and batteries only. Two optimization algorithms ABC and PSO have been applied along with software tool HOMER. Conventional PSO and ABC algorithms are simple and efficient. The control parameters for ABC and PSO algorithms have been shown in [Table 2.2](#). The stopping criterion is considered as maximum number of iterations which is taken 100 for both algorithms. A simulation is run for one hour interval data for one year on solar photovoltaic output, wind turbine output and electrical demand. The wind and solar power assumed to be constant during one hour duration. This system is designed for DC and AC bus voltages of 120 V. Hence, the PV panels and battery numbers connected in series are determined to fulfill the DC bus voltage. The number of batteries connected in series for desired voltage are 20 (Eq. no. (2.9)).

Table 2.2: Parameters of the PSO and ABC algorithms

ABC algorithm		PSO algorithm	
Dimension of the problem ( $D$ )	3	Dimension of the problem ( $D$ )	3
Employed bees=Onlooker bees	10	Population size ( $N$ )	20
Colony size ( $NP$ )	20	Initial weight ( $W_{min}$ )	0.4
Food number= 1/2 of the colony size ( $NP/2$ )	10	Final weight ( $W_{max}$ )	0.9
$Maxcycle$	100	Maximum number of iterations ( $It_{max}$ )	100
Limit	100	Weighting factors ( $C_1$ and $C_2$ )	2

[Table 2.3](#) shows the complete results obtained from the different algorithms. HOMER, ABC and PSO all find out optimal cost of the system while maintaining the LCOE of the system minimum. Results show optimal number of components, annualized system cost, total NPC and levelized cost of energy. It is inferred from the results that both evolutionary algorithm outperforms HOMER. The ABC algorithm performs slightly better than PSO in this case study. [Figure 2.6](#) shows convergence characteristics of the two algorithms. It can be concluded from the figure that PSO and ABC converges in the first 20 iterations. The optimization algorithms also take less computational time as compared to HOMER.

[Figure 2.7](#) demonstrates the optimal power management of the proposed system in

Table 2.3: Optimal sizing result received from various techniques

Algorithm	PV Units	Wind Turbine Units	Batteries Units	Inverter (kW)	ASC (\$/yr)	NPC (\$)	LCOE (\$/kWh)
HOMER	130	20	560	55	30,506	350,653	0.201
PSO	123	20	620	55	31,073	356,128	0.2038
ABC	142	12	560	55	30,395	348,806	0.1994

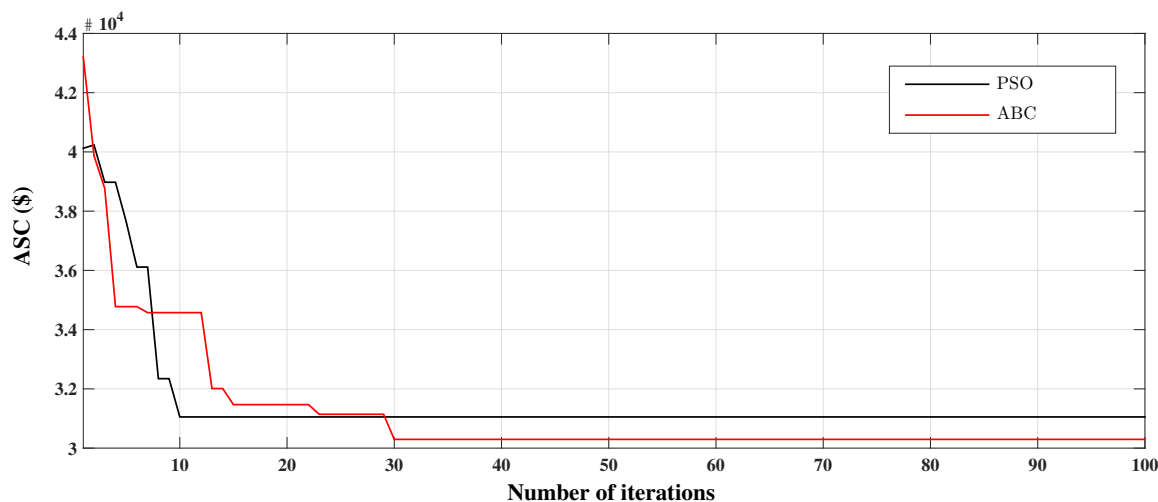


Figure 2.6: Convergence characteristic of the ABC and PSO algorithms

order to study the hourly power exchange between PV, wind, battery and load. The one day data is considered to analyze the energy use in the hybrid system. It is observed that load is served with any interruption. In such hybrid systems, where battery is used as storage, battery SOC measurement becomes an important issue. Figure 2.8 shows variations of the state of charge of the battery bank and also input and output energy throughout the year. The initial SOC level and minimum allowable SOC have been considered as 100% and 30%, respectively. Figure 2.8 demonstrates that battery SOC always remains in predefined limit. On 1st January, at hour 0000, initial SOC of the battery bank is considered to be 1,210 kWh (100%). It is evident from the Figure 2.8 that SOC is within predefined limit during whole year. Figure 2.8 also shows that most of time battery SOC is acceptable, except a few instances, such as in the case of the months June-July when the load demand is more. The charging and discharging rates of battery are other factors which required to be monitored continuously. For effective charging and discharging of the battery bank, maximum charging or discharging power ( $P_b^{max}$  for one hour interval) is 60.48 kW and it is calculated using Eq. (2.10). If the energy is available to charge beyond the charging rate it can be used as deferred load or it can be dumped. If

discharging energy is more than discharging rates of batteries, a diesel generator will be used as generating source.

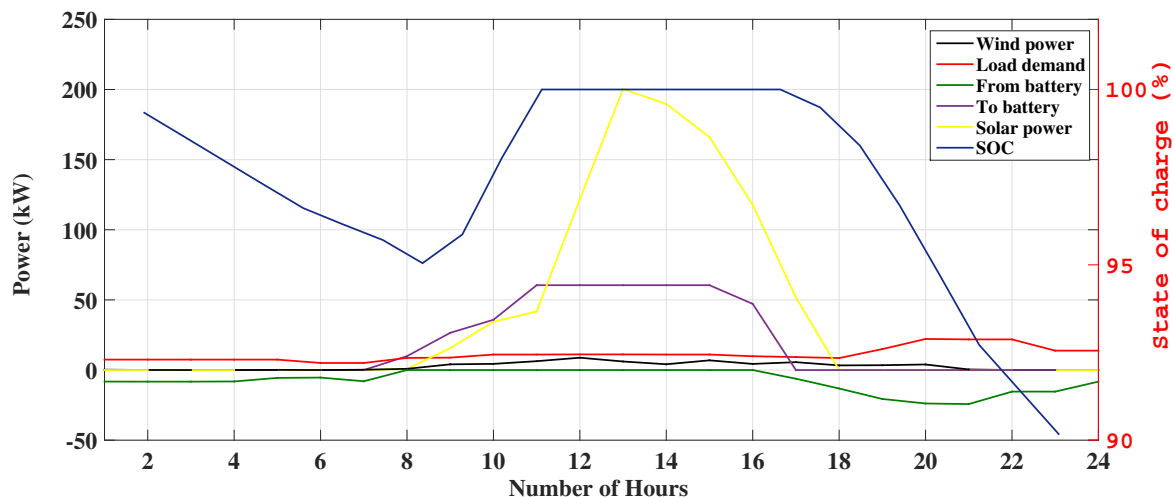


Figure 2.7: Power management indicating load demand, wind, solar, battery input/output and battery SOC (on secondary axis) power in case III of Table 2.4

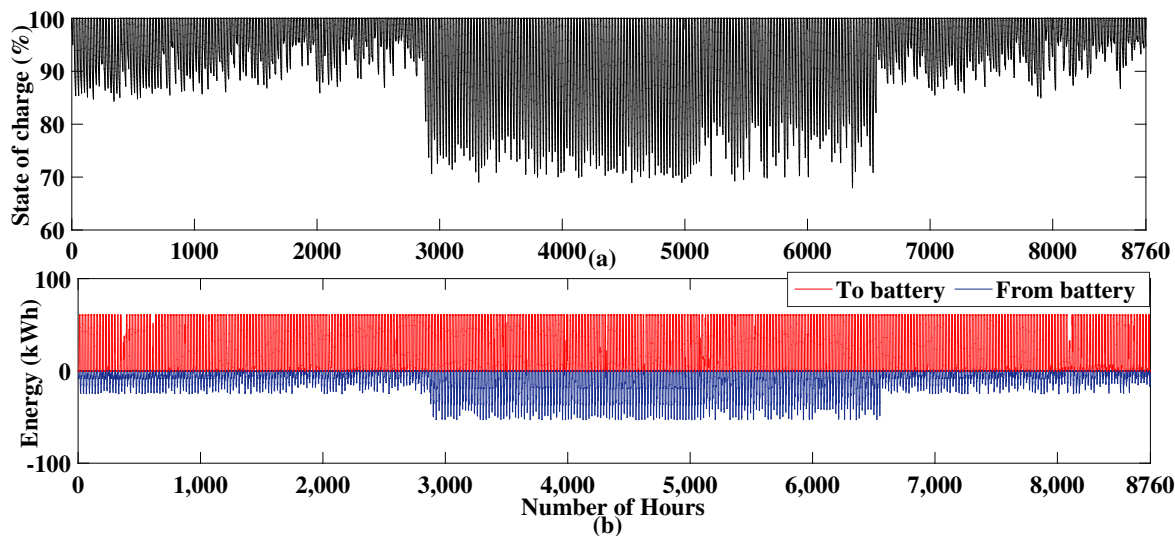


Figure 2.8: (a) Battery SOC (%) (b) Battery energy flow for one complete year

Further, results are obtained using HOMER software for different possible combination for cost analysis. Seven different possible combinations have been identified to meet the load demand of this particular area. The results have been sorted on the basis of least LCOE as demonstrated in Table 2.4. The highest LCOE of system is obtained when load is met only by diesel generator. High LCOE are due to high maintenance & operation cost and high replacement cost of the diesel generators. The lifetime of diesel generator depends upon the operating

Table 2.4: Optimal sizing result of different configurations obtained by HOMER

S.No.	Hybrid systems	PV Units	WT Units	Battery Units	DG (kW)	Inverter (kW)	ASC (\$/yr)	NPC (\$)	LCOE (\$/kWh)
1	PV+WT+B	130	20	560	-	55	30,570	350,653	0.201
2	PV+B	160	-	760	-	55	34,904	400,738	0.229
3	PV+WT+B+DG	198	20	440	20	55	36,656	420,856	0.241
4	PV+DG+B	200	-	680	50	55	41,419	475,541	0.262
5	WT+B	-	166	1,160	-	55	56,965	654,024	0.374
6	DG+B	-	-	80	48	55	515,750	5,921,363	3.360
7	DG only	-	-	-	48	-	658,226	6,582,263	3.765

WT: Wind turbine, B: Batteries, DG: Diesel generator, PV: Photo-voltaic

hours instead of life in years. Here, the lifetime of a diesel generator is 1.71 year (15,000 hours) is very less than the lifetime of the project, so nearly eleven replacement is required during the project time. It is also observed from these results that out of these seven scenarios hybrid solar-wind with battery is considered to be best one in terms of cost of energy. However, in terms of reliability hybrid system with diesel generator is still best, as diesel generator can be used a back up in case of failure of wind and solar sources.

## 2.6 Conclusion

As compared to standalone wind or standalone solar energy system, hybrid PV-wind-battery system is more reliable, economical and suitable source of electricity particularly to remote or off grid locations. The hybrid system possesses complex problem of designing, control, reliable due to varying weather conditions. In this chapter, a methodology has been developed to find out the optimal size of a hybrid PV-wind-battery system by using recently developed ABC algorithm. First modeling of different components like solar photo voltaic panels, wind turbine and batteries have been presented in brief. Then basic structure and flow chart of implementation of artificial bee colony have been discussed. Finally results obtained by ABC have been compared with results obtained by standard optimization tool HOMER. The proposed algorithm proved best results. In next chapter, ABC algorithm have been implemented in another hybrid system and further, a new renewable energy source biomass has been included in the hybrid configuration.

## Chapter 3

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### HYBRID SOLAR, WIND AND BIOMASS SYSTEM

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In the last few years, renewable based hybrid energy system, particularly, stand alone solar and wind based generation systems have become sustainable and environmentally friendly options to supply power in isolated or off grid locations. However, the biggest drawback of a stand alone solar-wind based energy system is its dependency on power back-up due to the irregular nature of both wind and solar resources. In case of a stand-alone hybrid system generally back-up is provided by diesel generator or energy storage devices such as batteries or ultra-capacitors. Usage of a diesel generator in hybrid system raises cost and environmental concerns. Fortunately, continuous advancement in technology, other renewable options such as biomass, bio-gas, mini hydro and fuel cell have been integrated along with solar and wind sources [Patil *et al.* (2010)].

In the aforementioned renewable energy options, biomass seems to be a more viable option, especially in the case of agriculture rich countries [Eziyi and Krothapalli (2014)]. Particularly in India, a huge crop residue is generated every year. Therefore biomass based power generation becomes one of threshold area of research in renewable energy sector in India [Hiloidhari *et al.* (2014)]. Biomass can be converted into many forms such as heat, electricity and bio-fuels [Singh *et al.* (2008)]. Due to advancement in biomass gasification technology, electricity generated by biomass gasifiers is becoming popular especially in the rural areas. Biomass power generation plants have high load factor and cost effective [Patil *et al.* (2011)]. Biomass power generation has been integrated along with PV, wind and other renewable energy sources. Stand alone and grid connected PV-biomass with or without storage is seen as a viable and cost effective option for electricity, particularly in developing countries [Bhattacharjee and Dey (2014)].

In India, the state of Punjab is having one of largest farming land. Punjab shares only 1.6% of the geographical area of the country, while it produces nearly 10% of rice, 13% of cot-

ton and 22% of wheat of the total production of these crops in the country. From these major crops, a total of 55.39 Metric tons agricultural residues is generated in the state and it is further estimated that 2000-3000 MW of electricity can be generated by using these agricultural residues [Singh *et al.* (2008), Chauhan (2012)]. Currently biggest drawback with these residues is inefficient usage. Most of agricultural residues are burnt in an open field after harvesting the crop which results air pollution, soil infertility and health hazards [Singh (2015), Sharma *et al.* (2010)].

Thus, utilizing locally available renewable energy sources for generation of electricity can be a possible option at off grid or electricity deficient places. In case of rural areas enough biomass, wind and solar resources are available. Therefore, electricity demands of such areas can be met by intelligently harnessing these resources. Moreover, in the case of renewable hybrid energy system, the power generated needs to be stored in a large battery bank [Mahapatra and Dasappa (2012)]. A typical self-sustainable hybrid energy system could be designed by incorporating renewable energy sources and storage systems. In case of such hybrid systems, various factors such as total cost of system, size and capacity of renewable energy sources plays a crucial role. Optimal power flow between different components of a hybrid system is required due to the intermittent nature of renewable energy sources. Two major parameters such as price of generating energy and reliability of the system are major challenges in hybrid systems. An optimal designed system should have the best selection of components while assuring the reliability of the system [Nehrir *et al.* (2011)].

In the existing literature, limited work has been found in PV, wind and biomass based hybrid systems with energy storage. For instance, Balamurugan *et al.* (2009) proposed a PV-biomass-wind hybrid system for rural areas of India. The authors performed economic analysis and component selection with the help of the standard software tool HOMER. Rahman *et al.* (2010) proposed a PV-biomass-wind based hybrid system for a location in Bangladesh. The system sizing was obtained with the help of HOMER. Dhass and Harikrishnan (2013) evaluated a PV-wind-biomass hybrid system for rural electrification on the basis of life cycle cost. Ho *et al.* (2014) integrated solar and biomass resources to make a small village self sustainable. To design hybrid system a mixed integer linear programming based model has been developed. Garrido *et al.* (2016) presented techno-economic analysis of hybrid PV-biomass energy system for an off grid location in Mozambique using tool HOMER. It is inferred from the results

that agricultural and food processing wastes could play an important role in energy generation, particularly in rural areas.

The aforementioned literature reveals that researchers have used either software tools or conventional optimization methods for performance analysis. However, software tools possess some serious disadvantages such as black box coding, single function minimization and require more computational time as compared to existing optimization techniques. However, many works have been identified in hybrid systems where the different researchers have proposed different conventional and evolutionary algorithms to achieve the optimal size of the components used in hybrid systems. In recent years, a new trend has been observed where researchers are applying widely evolutionary algorithms for optimal sizing of the hybrid energy system. To the best of authors knowledge, a very limited work is found, where the optimization of hybrid PV-wind-biomass along with the energy storage system has been explored.

From the above mentioned literature, it has been observed that there is a need of a hybrid system which consists of PV, wind and biomass along with an energy storage system especially in isolated or off-grid locations. The sizing of each equipments in any hybrid system is a challenging work. Despite of works in literature under different perspectives, the proposed work focuses on the hybrid energy system which is a combination of PV, wind, biomass and energy storage. The optimal sizing of components for all the above hybrid systems have been identified by using either software tools or by conventional and evolutionary algorithms. But none of the researchers have worked on the optimal sizing of PV-wind-biomass with battery bank as storage using evolutionary algorithms. The biomass resources can be harnessed along with wind and solar sources to enhance the reliability of the hybrid system. Therefore, in this work, an autonomous hybrid PV-wind-biomass with battery system is proposed to fulfill the electrical demand of a typical village. A swarm based meta-heuristic, ABC algorithm has been applied to realize optimal configurations of the proposed system. To compare the performance of the applied technique, the results achieved by the ABC algorithm have been compared with PSO and HOMER. A brief comparison is performed on the basis of the LCOE. The configuration with least LCOE is considered the optimal one. The main objectives of this chapter are outlined as follows.

- To develop a mathematical model of an autonomous PV-wind-biomass energy system with battery bank to provide electricity for an off-grid location.

- To deduce the optimal size of the components used in the proposed system with the least LCOE by minimizing the NPC of the system by applying swarm based ABC algorithm.
- To compare results achieved from the ABC algorithm to results obtained with HOMER and PSO.
- To observe the performance of the hybrid system in the critical cases such as failure of any generating unit.

The major contribution of this chapter is to design a cost effective and reliable hybrid PV-wind-biomass energy system with battery storage to meet the electrical load demand of small area which has enough natural resources. The mathematical modeling of various components and operational strategy in the proposed system have been discussed in detail. The detail cost analysis of the proposed hybrid system is performed by applying two evolutionary algorithms and one software tool. For optimal sizing and scheduling, results obtained by applying these different methods have been compared. Moreover, a critical case such as failure of one generating unit has also been performed to test the reliability of the hybrid energy system.

### **3.1 Mathematical modeling of proposed hybrid system**

This work emphasizes on the formulation of a new hybrid system to supply the reliable power to off-grid or isolated location. [Figure 3.1](#) shows the different components of the proposed microgrid. The power generated by wind, solar and biomass is managed with the help of storage devices. As shown in [Figure 3.1](#), load, wind turbines and biomass gasifier are connected to AC bus. Moreover, solar PV panels and batteries are connected to the AC bus via converters. A charge controller is also deployed to maintain the smooth flow of power and limit the charging and discharging rate of batteries.

The proposed system is most suitable for off grid locations and agriculture based villages in developing countries where energy crisis is a major concern. However, the proposed system can be integrated to the grid. This system will be helpful in reducing utility grid dependency as it is completely self sustaining with the renewable energy sources. For optimal distribution of power, battery banks are employed, which reduces intermittency of renewable energy sources. This work mainly emphasizes on optimal sizing of each component, while

guaranteeing the reliability of the system. The mathematical models of different components are discussed as follows.

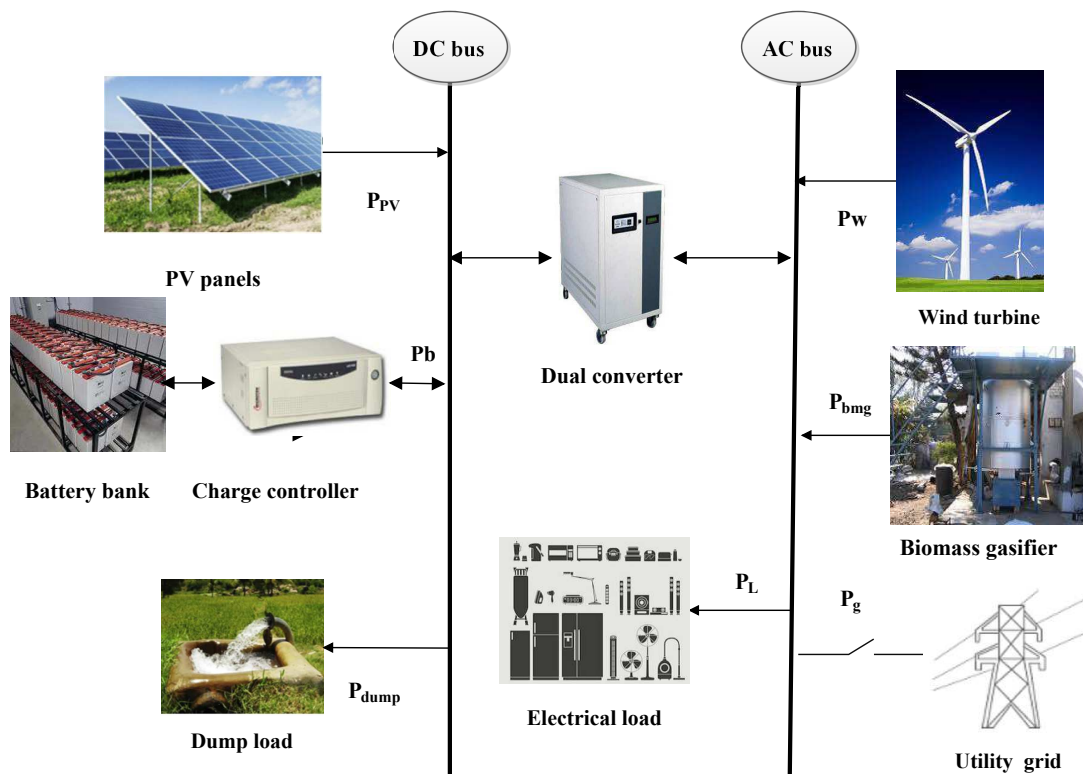


Figure 3.1: Different components of the proposed system

### 3.1.1 Biomass gasifier

In biomass gasification technology, solid bio-residue is transformed into a gaseous fuel which is finally used for electricity generation. Under partial combustion, the producer gas is produced which is a combustible gas with a composition of  $H_2$  (20%), CO (20%),  $CH_4$  (1-2%) and inert gases [Chauhan and Saini (2014)]. In case of biomass gasifier, the producer gas is used as an input fuel. The annual output electricity ( $E_{bmg}$ ) of a biomass gasifier can be computed as,

$$E_{bmg} = P_{bmg}(8760 * CUF) \quad (3.1)$$

where,  $P_{bmg}$  is rating of biomass gasifier system and  $CUF$  is the capacity utilization factor. In case of biomass based energy system, few parameters such as calorific value of biomass, availability of biomass (Ton/yr) and usage hours of biomass gasifier play important role. The

maximum rating of biomass gasifier installed in a particular area can be defined as follows,

$$P_{bmg}^m = \frac{\text{Total biomass available (Ton/yr)} * 1000 * CV_{bm} * \eta_{bmg}}{365 * 860 * \text{Operating hours/day}} \quad (3.2)$$

where,  $\eta_{bmg}$  represents overall biomass to electricity conversion efficiency and  $CV_{bm}$  is the biomass's calorific value [Gupta *et al.* (2010), Nouni *et al.* (2007)].

### 3.1.2 Battery bank

Batteries are used in hybrid renewable energy system to store excess energy and to discharge when power from renewable systems is insufficient or absent. The measurement of energy can be achieved with the proper estimation of the SOC. The SOC of the battery is a function of time and it can be calculated as,

$$\frac{SOC(t)}{SOC(t-1)} = \int_{t-1}^t \frac{P_b(t)\eta_{batt}}{V_{bus}} dt \quad (3.3)$$

where,  $V_{bus}$  is the voltage of bus,  $P_b(t)$  is battery's input/output power and  $\eta_{batt}$  is the round trip efficiency of the battery. If  $P_b(t)$  is positive, battery is charging, else it is discharging. Further, the round trip efficiency of a battery is defined as follows,

$$\eta_{batt} = \sqrt{\eta_{batt}^c \eta_{batt}^d} \quad (3.4)$$

where,  $\eta_{batt}^c$  and  $\eta_{batt}^d$  are charging and discharging efficiency of the battery respectively [HOMER (2016)]. The round trip efficiency of the battery bank is considered as 92.2%. Also, it is assumed that charging and discharging efficiencies are different and considered to be 85% and 100% respectively.  $SOC_{max}$  is the maximum value of SOC and is equal to the aggregate capacity of the battery bank ( $C_n(Ah)$ ) and it is given as follows,

$$C_n(Ah) = \frac{N_{batt}}{N_{batt}^s} C_b(Ah) \quad (3.5)$$

where,  $C_b(Ah)$  is the single battery capacity,  $N_{batt}$  is the total number of batteries,  $N_{batt}^s$  is the number of batteries connected in series. The battery bank can not discharge beyond a minimum limit which is called  $SOC_{min}$ . This limit can be used as system constraints according to the

usage of battery bank. To obtain desired bus voltage, batteries are connected in series. The number of batteries connected in series can be calculated as,

$$N_{batt}^s = \frac{V_{bus}}{V_{batt}} \quad (3.6)$$

where,  $V_{batt}$  is the voltage of a single battery.

Another major factor in battery modeling is the maximum charge or discharge power at any time. It depends upon maximum charge current, and can be calculated by the following equation,

$$P_b^{max} = \frac{N_{batt} V_{batt} I_{max}}{1000} \quad (3.7)$$

where,  $I_{max}$  is the battery's maximum charging current in amperes.

### 3.1.3 Power converter

DC/AC and AC/DC power converters are required when there are AC and DC components in the system. Solar PV panels and batteries are generating DC output while the considered load is AC. The converter size is chosen based upon peak load demand ( $P_L^m(t)$ ). The inverter rating ( $P_{inv}$ ) is calculated as follows,

$$P_{inv}(t) = P_L^m(t) / \eta_{inv} \quad (3.8)$$

where,  $\eta_{inv}$  denotes efficiency of the inverter. The rest of the components such as solar PV power, wind turbine power and power inverter have been modeled as already discussed in subsections 2.2.1, 2.2.2 and 2.2.5, respectively.

## 3.2 Problem formulation

The main objective of this study is to formulate a cost effective and reliable hybrid energy system. The rating and sizing of solar PV panels, wind turbine, battery bank and biomass gasifier are main decision variables. In this section, operational strategy of the system, objective function and brief introduction of applied algorithm is presented.

### 3.2.1 Operational strategy

In case of any hybrid energy system, proper power management is required to achieve reliability of the system. In this system, biomass gasifier is kept on least priority, i.e. it is run when solar, wind and batteries are unable to meet the load demand. Simplified steps of operational strategy are as follows

- If the total power produced by solar PV panels and wind turbines is sufficient and also wind power is less than load, then demand can be served by renewable sources only. After satisfying the load, surplus power can be provided to the battery bank and is given as,

$$P_b(t) = P_{PV}(t) - \{P_L(t) - P_w(t)\}/\eta_{inv} \quad (3.9)$$

where,  $P_L(t)$  denotes load demand at any time and  $\eta_{inv}$  denotes the efficiency of the inverter. If  $P_{sol}(t)$  is the power produced by an individual solar PV panel and  $N_{sol}$  is the total number of solar PV panels, then the total power produced by solar PV panels ( $P_{PV}(t)$ ) is given as

$$P_{PV}(t) = P_{sol}(t)N_{sol} \quad (3.10)$$

Further, if  $P_{wt}$  is the power produced by an individual wind turbine and  $N_{wt}$  is the total number of wind turbines, then the total power generated by wind turbines ( $P_w(t)$ ) can be given as,

$$P_w(t) = P_{wt}(t)N_{wt} \quad (3.11)$$

- If power generated solely from wind turbines is enough to supply load demand, the remaining power (solar & wind) can be fed to the battery bank. The battery power in this case can be calculated as,

$$P_b(t) = \{P_w(t) - P_L(t)\}\eta_{rec} + P_{PV}(t) \quad (3.12)$$

where  $\eta_{rec}$  is the rectifier efficiency.

- In both the above mentioned cases, if  $P_b(t)$  is greater than the maximum allowable capacity of battery bank ( $P_b^{max}$ ) then excess energy could be dumped or can be given to

deferrable loads. Excess or dump energy is obtained as,

$$P_{dump}(t) = P_b(t) - P_b^{max}(t) \quad (3.13)$$

- If solar PV panels and wind turbines are not generating adequate power, then balance power can be supplied by the battery and is calculated as,

$$P_b(t) = \{P_L(t) - P_w(t)\}\eta_{inv} - P_{PV}(t) \quad (3.14)$$

- If solar and wind power are inadequate and batteries  $\{SOC(t) \leq SOC_{min}\}$  are also not able to produce the desired power to meet the load demand, then biomass gasifier supplies power to the load.

1. First, load following strategy, i.e. whenever it operates, it generates only required power to meet the primary load demand. The power generated by the biomass gasifier is calculated as,

$$P_{bmg}(t) = P_L(t) - P_w(t) - P_{PV}(t)/\eta_{inv} \quad (3.15)$$

2. In second strategy, it operates at rated capacity or minimum load ratio. In case biomass gasifier is operating at rated capacity, the surplus power is used to charge the batteries and may be expressed as follows,

$$P_b(t) = \{P_{bmg}(t) - P_L(t) + P_w(t)\}\eta_{rec} + P_{PV}(t) \quad (3.16)$$

The energy management algorithm is demonstrated with the help of a simplified flow chart as shown in [Figure 3.2](#).

### 3.2.2 Objective function and constraints

The main motive of this study is to minimize total NPC of the proposed hybrid system while maintaining the optimal energy flow. For optimal configuration, four main decision factors, i.e., the number of wind turbines, solar PV panels, batteries and rating of biomass gasifier have

been selected. For the economic analysis, ASC concept is used. The result with least ASC is observed to be an optimal one while meeting all other constraints and parameters. The objective function considered is the total system cost, which consists of (i) total capital cost (ii) replacement cost and (iii) operational & maintenance cost of the components. Installation and civil works costs are incorporated in the capital costs of the components. The following function is considered as the main objective function which is to be minimized subject to constraints,

$$\text{Minimize : } ASC = F(N_{sol}C_{sol} + N_{wt}C_{wind} + N_{batt}C_{batt} + P_{bmg}C_{bmg} + P_{inv}C_{inv}) \quad (3.17)$$

where  $C_{sol}$ ,  $C_{wind}$ ,  $C_{batt}$  and  $C_{inv}$  are the cost of solar PV panel (per  $kW$ ), wind turbine (per  $kW$ ), battery (per unit) and inverter (per  $kW$ ) respectively.  $C_{bmg}$  is the cost of biomass gasifier (per  $kW$ ) and  $P_{bmg}$  is the rating of biomass gasifier.  $P_{inv}$  is the rating of the inverter.

The ASC of the installed component has several parts such as capital and installation cost ( $C_{acap}$ ), replacement cost ( $C_{arep}$ ), annual maintenance cost ( $C_m$ ), operation cost ( $C_f$ ) and salvage cost ( $C_{sal}$ ). Further, total ASC of each components can be expressed as follows,

$$C_{sol} = C_{sol}^{acap} + C_{sol}^{arep} + C_{sol}^m - C_{sol}^{sal} \quad (3.18)$$

$$C_{wind} = C_{wind}^{acap} + C_{wind}^{arep} + C_{wind}^m - C_{wind}^{sal} \quad (3.19)$$

$$C_{batt} = C_{batt}^{acap} + C_{batt}^{arep} + C_{batt}^m - C_{batt}^{sal} \quad (3.20)$$

$$C_{bmg} = C_{bmg}^{acap} + C_{bmg}^{arep} + C_{bmg}^m + C_{bmg}^f - C_{bmg}^{sal} \quad (3.21)$$

$$C_{inv} = C_{inv}^{acap} + C_{inv}^{arep} + C_{inv}^m - C_{inv}^{sal} \quad (3.22)$$

The annualized cost of any component can be calculated with the help of a factor CRF as defined in Eq. (2.15). CRF is used to compute present value of money. The objective function is minimized enforcing a set of several constraints, which are summarized as

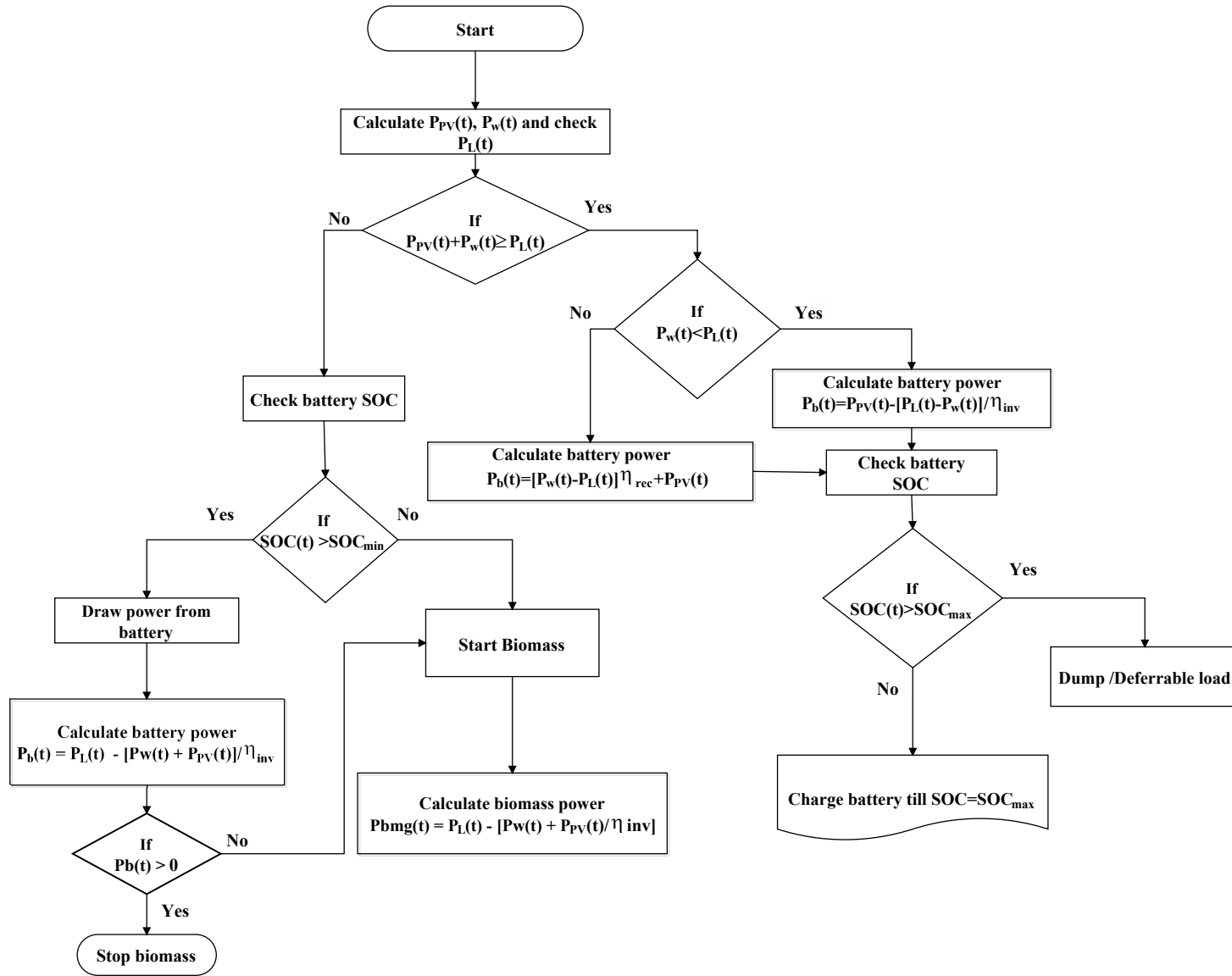


Figure 3.2: A simplified flow chart of the operating strategy of the proposed system

$$1 \leq N_{sol} \leq N_{sol}^m \quad (3.23)$$

$$1 \leq N_{wt} \leq N_{wt}^m \quad (3.24)$$

$$1 \leq P_{bmg} \leq P_{bmg}^m \quad (3.25)$$

$$1 \leq N_{batt} \leq N_{batt}^m \quad (3.26)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (3.27)$$

where,  $N_{sol}^m$  is the maximum number of solar PV panels,  $N_{batt}^m$  is the maximum number of batteries,  $N_{wt}^m$  is the maximum number of wind turbines and  $P_{bmg}^m$  is the maximum rating of biomass gasifier.

The optimal configuration is selected on the basis of LCOE and reliability. LCOE is declared as average price per  $kWh$  of the energy (useful) generated by the system and it is defined as per Eq. (2.18).

### 3.2.3 Artificial bee colony algorithm

The following steps are proposed to implement the ABC algorithm for the problem.

1. Input: Solar radiation data, wind speed data, biomass resource,  $P_L$  and components prices.
2. Output:  $(N_{sol}, N_{wt}, N_{batt}, P_{bmg})$
3. Store  $SOC_{max}, SOC_{min}, NP, D, FoodNumber, Maxcycle, Limit$
4. Store  $(N_{sol}^m=300), (N_w^m=20), (N_{batt}^m=1400)$  and  $(P_{bmg}^m=50)$
5. Compute  $P_{sol}(t)$  and  $P_{wt}(t)$  by using Eq. (2.20) and Eq. (2.21).
6. Generate a randomly initialized population as

$$P_{uv} = P_v^{min} + rand[0, 1](P_v^{max} - P_v^{min}) \quad (3.28)$$

7. Set trial counters to zero.

8. Calculate following for initial randomly generated solution ( $N_{sol}, N_{wt}, N_{batt}, P_{bmg}$ )
  - Compute  $P_{PV}(t)$  and  $P_w(t)$  using Eq. (2.20) and Eq. (2.21).
  - Perform the steps explained in operational strategy.
  - Calculate the component costs for initial solution by using Eq. (3.23) to Eq. (3.27).
9. Evaluate objective function F (Eq. (3.17)) for initial food source.
10. Calculate the fitness value for employed bees in the bee colony

$$fitness_i = \begin{cases} \frac{1}{1+f_i} & 0 \leq f_i \\ \frac{1}{1+abs(f_i)} & f_i \leq 0 \end{cases} \quad (3.29)$$

where,  $f_i$  is the evaluated cost value of the solution  $P_{uv}$ .

11. Cycle = 1.
12. Generate modified food location for the employed bees.

$$P_{uv}^{new} = P_{uv} + rand[-1, 1](P_{uv} - P_{wv}) \quad (3.30)$$

where,  $w = 1, 2, 3 \dots SN$  and  $v = 1, 2, 3 \dots D$  are randomly chosen index.  $w$  should not be equal to  $v$ .

13. Compute objective function F (Eq. (3.17)) by following step 8.
14. Apply greedy selection process
15. Compute probability value ( $p_i$ )

$$p_i = \frac{fit_i}{\sum_0^{SN} fit_i} \quad (3.31)$$

where,  $fit_i$  is the fitness value corresponding to  $i^{th}$  solution.

16. Generate new solutions ( $P_{uv}^{new}$ ) by using Eq. (3.30) for the onlookers bees on the basis of solutions selected according to the value of  $p_i$ .
17. Compute objective function F (Eq. (3.17)) for new solutions by following step 8.
18. Apply greedy selection process

19. Check if there are any abandoned solution for the scout, Eq. (3.28) for scouts to generate a new food source.
20. Remember and store the best solution gained so far.
21.  $Cycle = Cycle + 1$ .
22. Until,  $Cycle = Maxcycle$

### 3.3 Results and discussions

Methodology developed in this work has been employed to design a small stand-alone PV-wind-biomass-battery hybrid system as shown in Figure 3.1 to meet the electricity requirement of a small village, situated in Patiala, Punjab India. The case study area is situated at latitude  $30^{\circ}26'N$  and longitude  $76^{\circ}12'E$ . The scheme is basically designed for household loads of a small micro-grid having a peak load demand and load factor of 102 kW and 0.406 respectively. Two different kinds of load profile are considered on the basis of seasons, i.e., winter (October to April) and summer (May to September). This considered location has good availability of solar and wind resources throughout the year. From the existing data, it is found that the yearly average wind speed of this site is 5.9 m/s, while average solar radiation is found to be 5.14 kWh/m<sup>2</sup>/day. Figure 3.3 shows load profiles (winter and summer both), solar radiation and wind speed data considered for the study area. Table 3.1 shows detailed load demand for a small community having 110 households. This particular site had enough biomass feedstock to install a biomass gasifier. In Punjab, India the main crop residues are wheat and rice straw. It is estimated that these two crop residues contributes almost 75% of the total crop residues production in the state. The price of biomass, including transportation, storage and labor charges is considered to be \$25/ton [Singh et al. (2008)]. Economical and technical parameters associated with components used in this study have been presented in Table 3.2.

#### 3.3.1 Results analysis

The experimental results were simulated using HOMER and MATLAB 2014a program. The simulation time step is considered for one hour and run on a data for one year. The control parameters for ABC and PSO algorithms have been shown in Table 3.3. For the sake of

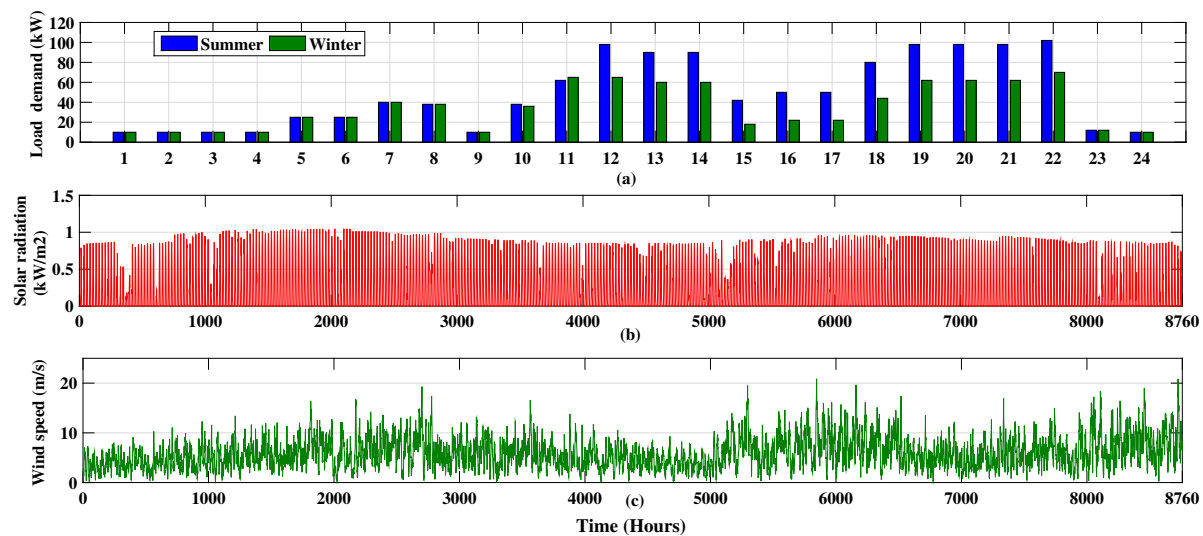


Figure 3.3: (a) Daily load profile (winter and summer ( $kW$ )) (b) Solar radiation ( $kW/m^2$ ) (c) Wind speed ( $m/s$ )

comparison of results, maximum number of solar PV panels ( $N_{sol}^m$ ), wind turbines ( $N_w^m$ ) and batteries ( $N_{batt}^m$ ) have been considered same for all the cases and taken as 300, 20 and 1400, respectively. The maximum rating of biomass gasifier ( $P_{bm}^m$ ) is considered to be 50  $kW$ . The size of inverter has not been included as decision variable. The rating of inverter has been selected on the basis of peak load demand using Eq. (3.8) and it has been considered as 115  $kW$ . In this proposed system, load following strategy is considered instead of cycle charging.

The results obtained from HOMER are taken as reference for comparison. The optimal results consist of total number of solar PV panels, wind turbines, batteries and a maximum rating of biomass gasifier. The feasible and optimal solution is ranked on the basis of ASC and LCOE. Table 3.4 shows complete optimized results obtained for the case study by HOMER, PSO and ABC algorithms. It is inferred from the results that ABC algorithm predicts minimum ASC of the system with least LCOE. The ABC algorithm predicts 250  $kW$  solar PV, 19  $kW$  wind turbines, 1400 batteries and 40  $kW$  biomass gasifier with ASC of 63,006  $\$/yr$  which results a LCOE of 0.173  $\$/kWh$ . It can be inferred from the table that both the meta-heuristic algorithms provide the same results. The performance of ABC algorithm is satisfactory as compared to PSO in terms of computational time and results. Moreover, both algorithms perform better than HOMER. It can be also noted that major contribution comes from solar energy in terms of capacity. The LCOE obtained by both algorithms shows that the proposed system provides energy to off grid location with an acceptable cost. The results show that ABC provides

Table 3.1: Estimated electricity demand for community

S.No	Type of load	Quantity	Power(W)	Summer (May-Sep)		Winter (Oct-April)	
				Hrs/day	Watt- hrs/day	Hrs/day	Watt- hrs/day
<b>A. Domestic load demand</b>							
1	CFL	4	23	10	920	6.5	600
2	CFL	1	11	8	88	11	121
3	Ceiling fan	1	120	20	2,400	0	0
4	kitchen fan	1	30	6	180	0	0
5	Cooler	2	120	10.5	2,520	0	0
6	Television	1	100	9	900	6	600
7	Computer	1	300	8	2,400	9	2,700
8	Exhaust fan	1	15	5	75	3	45
9	Table fan	1	15	8	120	0	0
10	Room heater	1	90	0	0	12	1,080
11	Room heater	1	150	0	0	7	1,050
12	Electric blanket	1	120	0	0	3	360
13	Vacuum cleaner	1	220	2	440	1	220
14	Bulb	1	100	1	100	2	200
	Total (one house)				10,143		6,976
	No. of Houses	110					
	<b>Total demand (A) (kWh/d)</b>				1,115.73		767.36
<b>B. Community load demand</b>							
1	Shops	4	400	12	4,800	12	4,800
2	Community shop	2	200	3	600	5	1,000
3	Community center	1	1,000	7	7,000	7	7,000
4	Small industry	1	3,000	8	24,000	8	24,000
5	Hospital	1	3,000	9	27,000	9	27,000
6	Elementary school	1	1,500	11	16,500	11	16,500
7	Street light	5	30	9	270	12	360
	Total demand (B) (kWh/d)				80.17		80.66
	<b>Total demand (A+B) (kWh/d)</b>				1,195.9		848.02

an optimal configuration with least LCOE. Therefore, for detailed economic and reliability discussion, results obtained by the ABC algorithm may be chosen as an optimal combination.

Table 3.5 demonstrates complete and detailed annualized cost analysis of the optimal hybrid system. The annualized costs are calculated with the help of CRF. The lifetime of solar PV panels, wind turbines and inverter are considered same as project lifetime, so no replacement is required in their case. The lifetime of biomass gasifier depends upon the operating

Table 3.2: Technical and economical data of the components

Component	Parameter	Value	Unit
<b>Biomass gasifier</b>	Rated power ( $P_{bmg}^m$ )	50	$kW$
	Calorific value of biomass ( $CV_{bm}$ )	18	$MJ/Kg$
	Conversion efficiency ( $\eta_{bmg}$ )	21	%
	Capital cost (per $kW$ )	2,300	$$/kW$
	Replacement cost (per $kW$ )	1,500	$$/kW$
	O & M cost (per $kW$ )	2	$$/yr$
	Life time	15,000	hours
<b>Converter</b>	Rated power	115	$kW$
	Rectifier ( $\eta_{rec}$ ) and inverter ( $\eta_{inv}$ ) efficiency	90	%
	Replacement cost (per $kW$ )	127	$$/kW$
	O & M cost (per $kW$ )	1	$$/yr$
	Life time	20	years
<b>Other</b>	Interest rate ( $r$ )	6	%
	Project life ( $n$ )	20	years
	Bus voltage (DC) ( $V_{bus}$ )	120	$V$
	Batteries in string ( $N_{batt}^s$ )	20	units

Table 3.3: Parameters of the PSO and ABC algorithms

ABC algorithm		PSO algorithm	
Dimension of the problem ( $D$ )	4	Dimension of the problem ( $D$ )	4
Employed bees=Onlooker bees	10	Population size ( $N$ )	20
Colony size ( $NP$ )	20	Initial weight ( $W_{min}$ )	0.4
Food number= 1/2 of the colony size ( $NP/2$ )	10	Final weight ( $W_{max}$ )	0.9
$Maxcycle$	100	Maximum number of iterations ( $It_{max}$ )	100
Limit:	100	Weighting factors ( $C_1$ and $C_2$ )	2

hours instead of life in years. Here, the lifetime of biomass gasifier is more than the lifetime of the project, so no replacement is required. The main component which required replacement is battery bank. It is assumed that the set of batteries need replacement in every five years. So the number of replacements of batteries during project life is 3. Batteries consist of 44% of the total cost of the system. The results predict that solar PV contributes 43%, wind turbines 6% and biomass gasifier cost 4.5 % of total annual costs. Figure 3.4 demonstrates a brief comparison between the convergence rates of both algorithms. It can be seen from the figure that both algorithms converge in almost initial 10 iterations. HOMER software took hours to simulate the proposed system, while algorithms reduce simulation time from hours to minutes. Table

Table 3.4: Optimal sizing result received from various techniques

Algorithm	PV	Wind Turbine	Biomass gasifier	Batteries	Inverter	Biomass running	ASC	NPC	LCOE
	(Units)	(Units)	(kW)	Units	(kW)	(hours)	(\$/yr)	(\$)	(\$/kWh)
HOMER	280	18	50	1200	115	18	65,573	7,52,118	0.181
PSO	251	20	43	1400	115	35	63,584	7,30,011	0.176
ABC	250	19	40	1400	115	10	63,006	7,23,378	0.173

3.6 shows a brief comparison of energy production by all components for the configurations obtained by HOMER, PSO and ABC. The results obtained from both the algorithms emphasize on usage of more battery power as compared to HOMER. The proposed system satisfies total

Table 3.5: Break down of ASC obtained by the ABC algorithm for the proposed system

Component	Capital	Replacement	Maintenance cost	Fuel	Salvage	Total
	(\$/yr)	(\$/yr)	(\$/yr)	(\$/yr)	(\$/yr)	(\$/yr)
PV	26,155	0	1,000	-	-	27,155
Biomass	3,487	-	80	286	-1,071	2,782
Wind turbines	3,809	-	38	-	-	3,847
Batteries	20,384	5,111	2,338	-	-	27,833
Inverter	1,273	-	115	-	-	1,388
Total	55,108	5,111	3,571	286	-1,071	63,006

Table 3.6: Energy analysis by HOMER, PSO and ABC algorithm

	HOMER	PSO	ABC
	kWh/yr	kWh/yr	kWh/yr
Solar	518,786	465,054	463,201
Biomass	572	891	326
Wind	72,009	80,010	76,009
Battery In	198,910	292,780	302,796
Battery Out	169,348	167,712	169,766
Total demand served	362,795	362,795	362,795
Excess electricity	165,941	3,513	5,139

energy demand with the help of solar, wind and batteries only. Figure 3.5 demonstrates the monthly average energy balance for one year. It can be noted that solar and wind powers have been consistent with the available solar and wind resources. In the month of January, when PV panels are generating less power, biomass gasifier is run to fulfill the load demand. During the rest of the month, good amount of solar power is generated due to better availability of natural

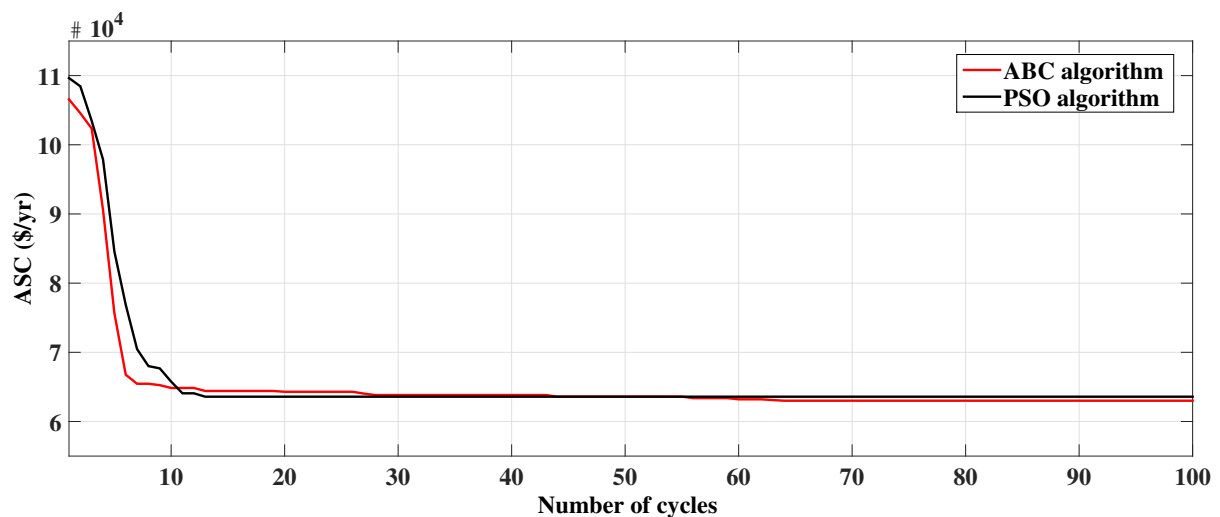


Figure 3.4: Comparison of convergence rates for PSO and ABC algorithms

resources. However, during summers, utilization of battery bank increases, i.e., more power is drawn from the batteries. It can be also seen from the figure that there are only three months, where excess energy is available. This system is designed to minimize the dumped or excess energy. It can be noted from the Table 3.6 that total excess energy during the complete year is found to be 5,139 kWh/yr, which results in 1.4% of the load served. On the contrary, in case of HOMER, this excess energy is found to be 165,941 kWh/yr, which accounts 45% of total load served.

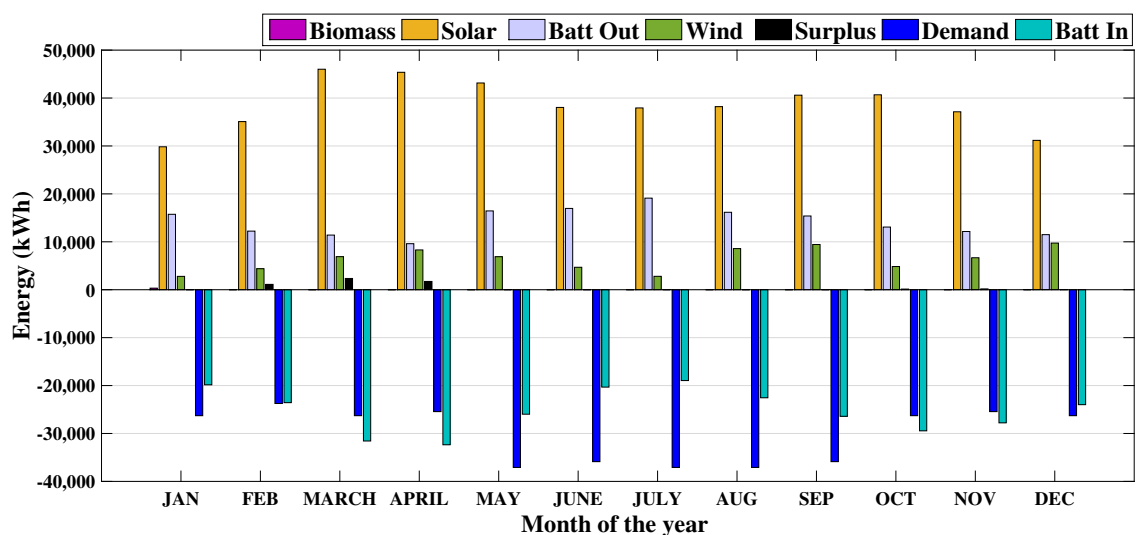


Figure 3.5: Monthly energy analysis for the proposed case study

To verify the optimal operation of the proposed system for one year a total period of two weeks have been selected, i.e., one week in January where the load is less and second

week in June where load demand is more. [Figure 3.6](#) shows a complete power exchange for one week in the month of January in order to understand the power exchange between different components of the system. As discussed in the operational methodology, a biomass gasifier is run when power from solar and wind is deficient and batteries are equal or below  $SOC_{min}$  (30%). It can be seen from figure that in the month of January, for a few hours (0050 to 0091) solar and wind power generation is less and also battery SOC are approaching  $SOC_{min}$ . So during these hours, biomass gasifier is run to provide power to the system. [Figure 3.7](#) demonstrates the energy management for the last week of June. It can be inferred from the [Figure 3.7](#) that enough solar power is generated due to better availability of the solar resource. No biomass power is required as the total load demand is met with the help of batteries, solar and wind only.

Particularly, in systems using battery as storage, battery SOC measurement becomes an important issue. [Figure 3.8](#) shows variations of the state of charge of the battery bank and also input and output energy throughout the year. The initial SOC level and minimum allowable SOC have been considered as 100% and 30%, respectively. [Figure 3.8](#) demonstrates that battery SOC always remains in predefined limit. On 1st January, at hour 0000, initial SOC of the battery bank is considered to be 3,014 kWh (100%). It is evident from the [Figure 3.8](#) that SOC reached a minimum of 907.2 kWh (30%) during a few hours in the whole year. [Figure 3.8](#) also shows that most of time battery SOC is good, except a few instances, such as in the month of January when natural resources are low, and in the case of the months June-July when the load demand is more. The charging and discharging rates of battery are other factors which required to be monitored continuously. For effective charging and discharging of the battery bank, maximum charging or discharging power ( $P_b^{max}$  for one hour interval) is 151.2 kW and it is calculated using Eq. (3.7). If the energy is available to charge beyond the charging rate it can be used as deferred load or it can be dumped. If discharging energy is more than discharging rates of batteries, a biomass gasifier will be used as generating source.

### 3.3.2 Robustness test

In order to verify the effectiveness of ABC and PSO algorithms, total 30 number of independent runs have been performed for each algorithm. [Table 3.7](#) shows mean, maximum and minimum value of ASC and standard deviation for 30 runs. It is evident from the table that the ABC al-

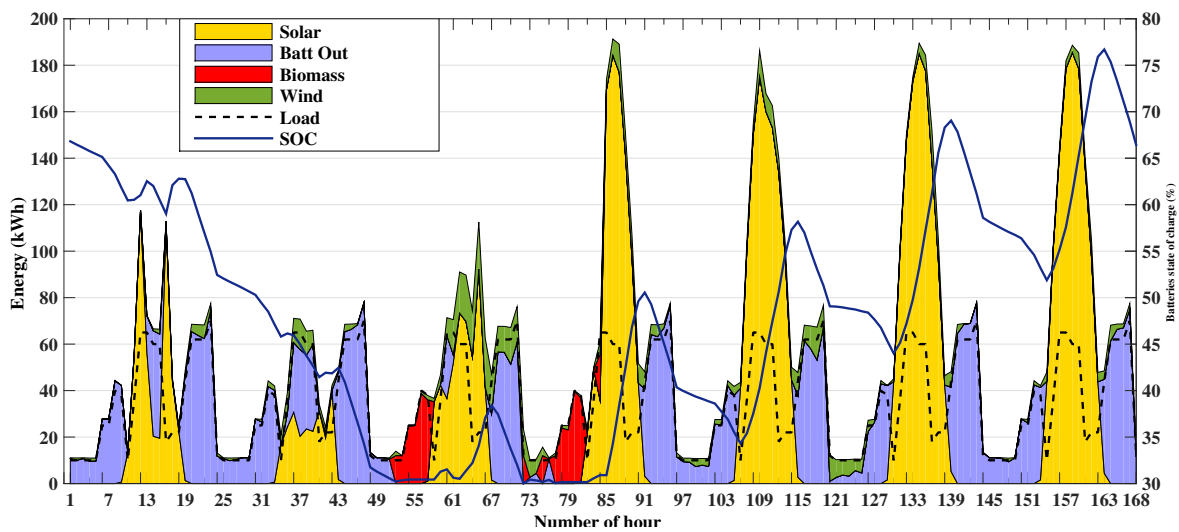


Figure 3.6: Energy balance and battery SOC for the third week of January

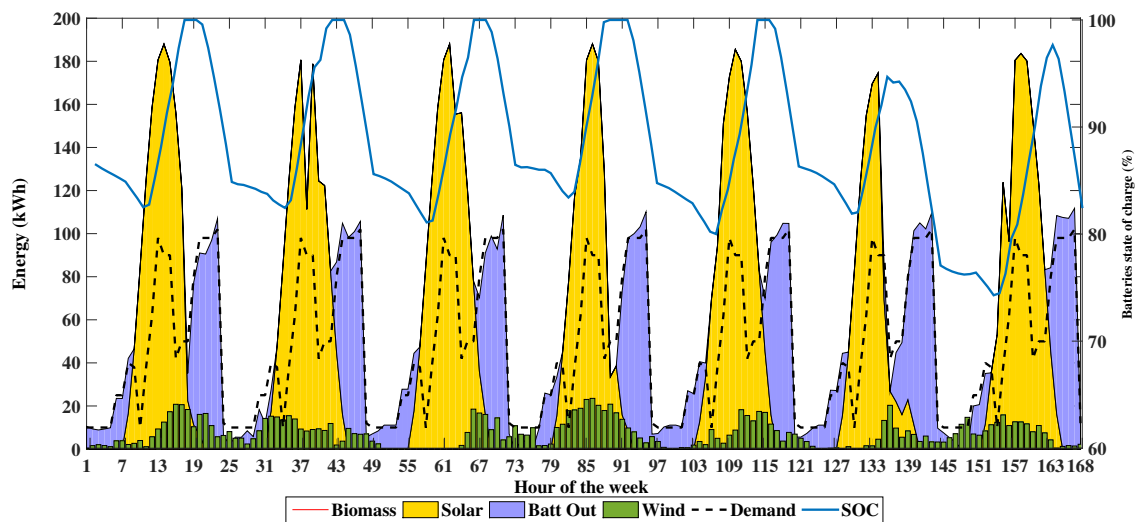


Figure 3.7: Energy balance (on left y axis) and battery SOC (on right y axis) for the last week of June

gorithm shows minimum deviation, which makes ABC better than the PSO algorithm. Further, paired student's t-test is performed to validate the effectiveness of results at 5% confidence level. The ASC achieved by the ABC algorithm is significantly less than ASC achieved using PSO algorithm. The reason being that the p-value ( $4.22 \times 10^{-10}$ ) is less than 0.05, when paired student's t-test is performed on both the algorithms (Table 3.8). The p-value less than 0.05 indicates that there is a substantial difference between the outcomes of the ABC and PSO algorithms.

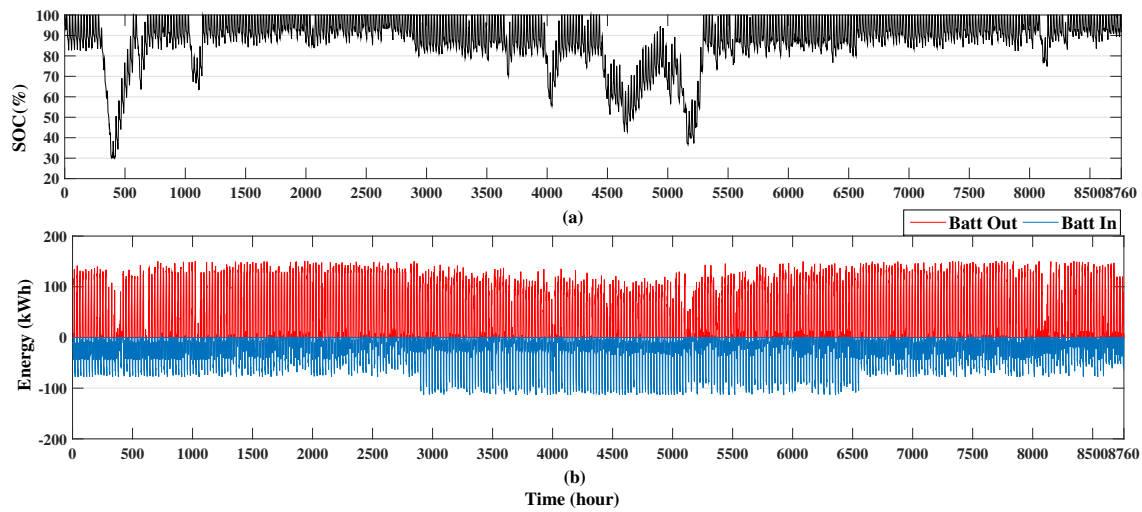


Figure 3.8: (a) Battery SOC (%) (b) Battery energy flow for one complete year

Table 3.7: Statistics of the results obtained by ABC and PSO algorithms

Algorithm	Mean Value	Minimum value	Maximum value	Standard deviation
ABC	64,180.05	63,006	64,755.6	293.44
PSO	64,855.00	63,584	65,345.9	359.04

Table 3.8: Paired student's t-test results for sample mean

Statistics	System
p-value	$4.22 * 10^{-10}$
t-calculated	7.26
t-critical	1.67

### 3.3.3 A special case: failure of one source

In this subsection, the effect of failure of any generating unit of the system is discussed to analyze the performance and reliability of the system. For instance, failure of wind source in the month of June is considered. The failure of any generating unit creates a supply-load imbalance in any system. Figure 3.9 shows a complete power exchange for one week in the last week of June, while keeping optimized parameters same. It can be seen from the Figure 3.7 that previously biomass gasifier was not run in the month of June, while failure of wind power forces biomass gasifier to run several times. It can be noted from the Figure 3.9 that if SOC's of the batteries are less than their critical values, i.e. 30%, the biomass gasifier starts and provides power. The biomass running hours increase from 10 to 45 hours and total power generated by biomass also increase from 325 kWh to 1,091 kWh. Also, due to more usages of biomass gasifier, total ASC of system increases from 63,006 \$/yr to 63,416 \$/yr, which makes LCOE

slightly costlier.

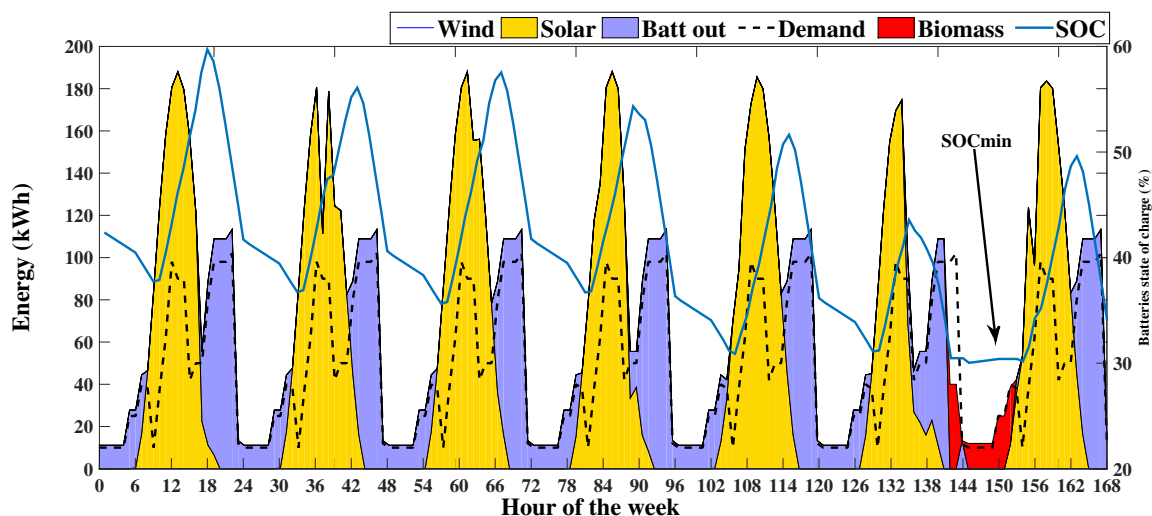


Figure 3.9: Solar, wind, battery, biomass energy, load demand and battery SOC (on right y axis) for the last week of June

### 3.3.4 Effect of the battery’s efficiency on LCOE

In this subsection, the effect of battery’s round trip efficiency on LCOE has been performed. In the previous section the results were obtained with a round trip efficiency of 92.2 % while the charging and discharging efficiencies were considered as 85 % and 100% for results analysis. However, to make the study more realistic the charging and discharging efficiencies have been considered to be same. The results for different round trip efficiency by keeping similar charging and discharging efficiencies has been plotted in the [Figure 3.10](#). It has been found that as the round trip efficiency increases the LCOE decreases drastically.

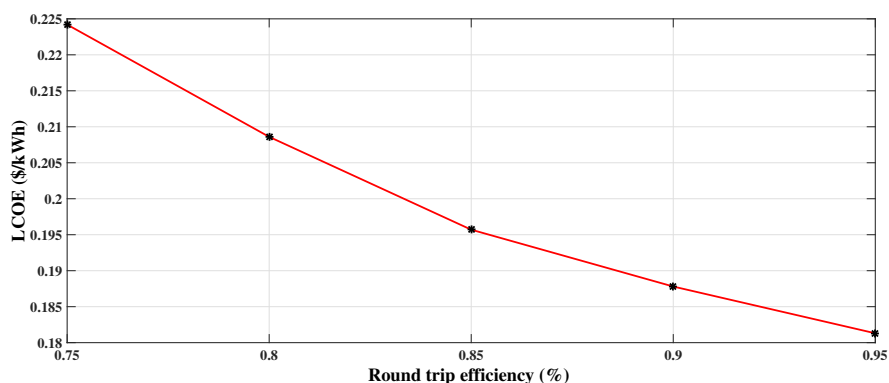


Figure 3.10: Effect of battery’s round trip efficiency on LCOE

### 3.4 Conclusion

A hybrid energy system is more reliable, economical and suitable source of electricity, particularly for off grid locations. In this chapter, a mathematical model has been developed to find the optimal size of components of a hybrid PV-wind-battery with biomass by applying the ABC algorithm. Initially, mathematical modeling of different components used in the study is discussed in brief, later on operational strategy and implementation steps of the ABC algorithm has been presented. Finally, results deduced by ABC algorithm have been compared with results obtained by software tool HOMER and other meta-heuristic algorithm PSO. The proposed algorithm proved better results as compared to HOMER and PSO. The performance of the proposed hybrid system is analyzed by considering failure of one generation unit. It can be concluded from the study that optimal hybrid system satisfactorily satisfy the load demand without violating any constraints.

## Chapter 4

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### GRID INTEGRATED PV-BIOMASS SYSTEM

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#### 4.1 Introduction

Renewable based hybrid energy systems have received great attention in recent years as they appears one of the clean source of electricity generation. The major issues while designing of renewable based hybrid system are power management, reliability of the system and economic cost of energy. The designed system must be optimal in terms of performance and component selection. Hence, the proper optimal sizing method and control scheme are required to plan an effective and economical hybrid system. Among the available renewable energy sources, solar and biomass based systems have tremendous potential for rural electrification [[Banerjee \(2006\)](#)]. In recent years, feasibility of various solar and biomass energy based systems have been explored for rural electrification by various researchers [[Kumaravel and Ashok \(2012\)](#), [Neto \*et al.\* \(2010\)](#), [Heydari and Askarzadeh \(2016a\)](#), [Heydari and Askarzadeh \(2016b\)](#)]. Most of the studies have paid much attention on modeling of off-grid renewable hybrid energy systems. Integration of renewable energy sources to the grid is a challenging job because of the intermittent nature of renewable energy sources. The grid connection provides a back up to the hybrid system, which eliminates the need of batteries and diesel generators. A few studies have been reported so far in the literature for PV-biomass grid connected system. Most of the works carried out the feasibility studies of grid connected PV-biomass hybrid energy system using software tool HOMER for performance and optimization. Mathematical modeling of grid connected PV-biomass energy system is neglected by the researchers. Therefore, to overcome this shortcoming, this work mainly focuses on detailed mathematical modeling of grid connected PV-biomass hybrid energy system. This study intends to provide a detailed cost analysis of a grid connected PV-biomass hybrid energy system to supply uninterrupted electricity to a village using ABC algorithm. The main objectives of this chapter can be summed up as below

- Developing a mathematical model of a grid connected PV-biomass hybrid energy system by exploiting locally available natural resources to fulfill the electricity demands of a small area.
- Performing comparative analysis between a swarm based ABC algorithm and HOMER for cost effectiveness of a grid connected and stand-alone hybrid PV-biomass energy system.
- Finding of optimal sizing of components with the least levelized cost of energy by minimizing the annualized cost of the total system.
- Performing sensitivity analyses for different parameters, like grid sale capacity with respect to the LCOE and other parameters.

This chapter presents an optimal sizing methodology for a stand-alone and grid connected PV-biomass hybrid energy system that serves the electricity demand of a typical village. However, this method is scalable and can be used in any test system. A recently developed artificial bee colony algorithm is used to detect out the optimum hybrid system configuration with the least levelized cost of energy while minimizing annualized system cost. It has been observed from the results that a grid connected hybrid PV-biomass system is cost effective and reliable choice for rural electrification as compared to stand-alone hybrid PV-biomass energy system. It has been emerged from this study that the proposed system offers reliable and affordable electricity in a sustainable way by harnessing locally available natural resources. A brief comparison of results obtained from the ABC algorithm and HOMER have been carried out. Moreover, it is also observed from the results that the ABC algorithm provides better results as compared to HOMER.

### **4.2 Mathematical modeling of the hybrid system**

The proposed grid connected hybrid renewable generation system consists of different components such as solar PV panels, power inverter, biomass gasifier with generator and utility grid as shown in [Figure 4.1](#). The diesel generator is kept optional and it will be used as back-up for overcast situations and outages etc. The power generated from renewable sources is assumed to be constant during one hour duration. The mathematical modeling of different components

of the proposed hybrid energy system in order to analyze the system performance is presented in this section.

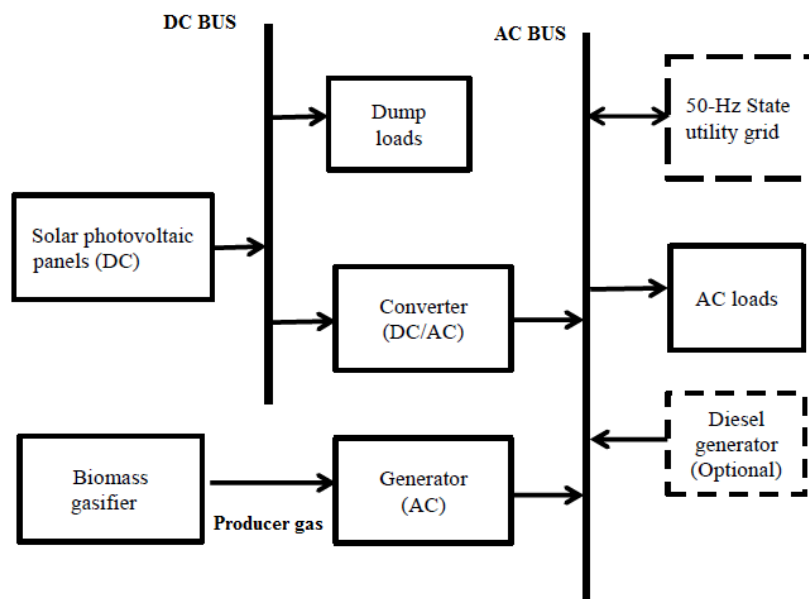


Figure 4.1: Schematic diagram of the proposed hybrid grid connected PV-biomass energy system

### 4.2.1 Power inverter

The power inverter is used to convert DC generated by solar PV panels to AC at the desired frequency to serve the AC load. The maximum power an inverter can convert depends upon the inverter rating ( $P_{inv}$ ). Further, it can be calculated as,

$$P_{inv}(t) = P_{PV}(t)\eta_{inv} \quad (4.1)$$

where,  $\eta_{inv}$  is the efficiency of the inverter and  $P_{PV}$  is the total power generated by solar PV panels and can be calculated as,

$$P_{PV}(t) = P_{sol}(t)N_{sol} \quad (4.2)$$

where,  $P_{sol}(t)$  is the power generated by a single solar PV panel and  $N_{sol}$  is the number of solar PV panels. In a grid connected system, the maximum size of inverter depends upon grid sale

capacity and load served and can be expressed as,

$$P_{inv}^{max}(t) = P_L^{max}(t) + P_{gs}^{max} \quad (4.3)$$

where,  $P_L^{max}(t)$  is the peak load demand at day time ( $kW$ ) and  $P_{gs}^{max}$  is the maximum capacity of power sold to the grid ( $kW$ ).

### 4.2.2 Utility grid

In a grid connected system, if the power generated from renewable sources is more than load, then the remaining power can be supplied to the grid. The power which can be supplied to the grid,  $P_{gs}(t)$ , can be calculated as,

$$P_{gs}(t) = \{P_{PV}(t)\eta_{inv} + P_{bg}(t)\} - P_L(t) \quad (4.4)$$

The maximum amount of power which can be supplied to the grid should not exceed maximum grid sale capacity ( $P_{gs}^{max}$ ). At any instant, if the power exceeds from maximum grid sale capacity, the surplus power can be given to the dump load.

If the power generated from renewable energy sources is not enough to meet the electricity demand, then power can be supplied by the grid. The amount of power that can be supplied by the grid,  $P_{gp}(t)$ , can be calculated as,

$$P_{gp}(t) = P_L(t) - \{P_{PV}(t)\eta_{inv} + P_{bg}(t)\} \quad (4.5)$$

Further, the maximum amount of power which can be supplied by the grid should not exceed maximum grid purchase capacity ( $P_{gp}^{max}$ ).

The rest of the components such as solar photovoltaic and biomass gasifier power have been modeled as already discussed in subsection 2.2.1 and 3.1.1, respectively.

## 4.3 Problem formulation

The main objective of this work is to design and model a grid connected PV-biomass hybrid energy system as shown in Figure 4.1 In order to verify the cost effectiveness of the proposed

model, the ABC algorithm and HOMER are used to find out the optimal number of solar PV panels and size of the biomass gasifier system. It is also ensured that LCOE of the system is minimized subject to the constraints that electricity demand of the area is completely satisfied. In this work, the concept of the annualized cost of the system has been adopted. The objective function, operational strategy and implementation of the applied algorithm are hereby explained in brief.

### 4.3.1 Objective function

The main objective function considered in this work is the minimization of total system cost of the proposed hybrid energy system. The total system cost includes total capital cost, replacement cost, operational and maintenance cost, grid sale and purchase power costs. Installation and other costs are included in the capital cost. The system with lowest ASC is considered optimal one while satisfying other constraints. The objective function which has to be minimized can be expressed as follows,

$$\min(ASC) = [N_{sol}C_{sol} + P_{bg}C_{bg} + P_{inv}C_{inv} - C_{gs} + C_{gp}] \quad (4.6)$$

where,  $C_{sol}$ ,  $C_{bg}$  and  $C_{inv}$  are the annualized total cost of solar PV panel (per  $kW$ ), biomass gasifier (per  $kW$ ) and power inverter (per  $kW$ ) respectively.  $C_{gp}$  is the total price ( $\$/yr$ ) of electricity purchased from grid annually (refer Eq. (4.15)) and  $C_{gs}$  is the total price of electricity sold to the grid ( $\$/yr$ ) annually (refer Eq. (4.17)).

The annualized cost of each component comprises several components i.e. annualized capital cost, annualized operational and maintenance cost, annualized replacement cost and salvage value. The cost analysis is further explained in detail in the case of the biomass gasifier system which possess all kinds of costs. Annualized cost of biomass gasifier system,  $C_{bg}$ , includes five components and can be expressed as,

$$C_{bg} = C_{acap}^{bg} + C_{arep}^{bg} + C_m^{bg} + C_f^{bg} + C_{sal}^{bg} \quad (4.7)$$

where,  $C_{acap}^{bg}$  is the annualized capital cost,  $C_{arep}^{bg}$  is the annualized replacement cost,  $C_m^{bg}$  is the annual maintenance cost,  $C_f^{bg}$  is the operational (fuel) cost and  $C_{sal}^{bg}$  is the salvage value of the biomass gasifier system.

### Annualized capital cost

The capital cost of the component includes the cost of installing and purchasing of components. The annualized capital cost of each component (solar PV panels, biomass gasifier and power inverter) can be calculated by using CRF. For example, in case of biomass gasifier it can be calculated as,

$$C_{acap}^{bg} = C_{cap}^{bg} CRF(r, n) \quad (4.8)$$

where,  $C_{cap}^{bg}$  is the initial capital cost of the biomass gasifier system. CRF can be calculated as Eq. (2.15)

### Annualized replacement cost

The annualized replacement cost of the biomass gasifier system is the cost of replacing at the end of life of the biomass gasifier system. The annualized value of total replacement cost,  $C_{arep}^{bg}$ , which occurred during the lifetime of a project life can be given as,

$$C_{arep}^{bg} = C_{rep}^{bg} CRF(r, n) \frac{1}{(1+r)^y} \quad (4.9)$$

where,  $C_{rep}^{bg}$  is the replacement cost of the component and  $y$  is the lifetime of the biomass gasifier system in years. The replacements are required if the lifetime of the project is greater than component lifetime. In case of a biomass generator, lifetime is the number of running hours. The lifetime (number of years) of a biomass gasifier can be calculated as,

$$N_{bg,l} = \frac{N_{bg,h}}{N_{bg}} \quad (4.10)$$

where,  $N_{bg,h}$  is the generator lifetime (hours) and  $N_{bg}$  is the number of hours operating during one year.

### Maintenance cost

The maintenance cost per hours of biomass gasifier system includes labour costs, repairing and other charges to operate the biomass gasifier and can be expressed as,

$$C_m^{bg} = N_{bg} C_m^h \quad (4.11)$$

where,  $N_{bg}$  is the hours of running of biomass gasifier and  $C_m^h$  is the hourly maintenance cost of the biomass gasifier system.

### Fuel cost

In case of biomass gasifier system, the biomass cost is equal to the amount of biomass feedstock consumed over a year (in  $kg$ ) multiplied by the price of biomass ( $\$/kg$ ). The total cost of biomass used can be calculated as,

$$C_f^{bg} = E_{bg} C_b q(t) \quad (4.12)$$

where,  $C_b$  is the price of biomass per  $kg$ ,  $E_{bg}$  is the total energy generated by biomass gasifier in ( $kWh/yr$ ) and  $q(t)$  is the rate of biomass consumed ( $kg/kWh$ ) for the biomass gasifier system.

### Salvage value

It is defined as the value remaining of a component at the end of project life. The salvage value of the biomass gasifier can be calculated as,

$$C_{sal}^{bg} = C_{rep}^{bg} \frac{R_{rem}}{N_{bg,l}} \quad (4.13)$$

where,  $C_{rep}^{bg}$  is the replacement cost of the component,  $R_{rem}$  is the remaining life of the biomass gasifier system and  $N_{bg,l}$  is the life span of the biomass gasifier system.

In the grid connected systems, apart from the components related costs the price of power exchange between the hybrid system and utility grid are other major economic components as brought up in the main objective function defined in Eq. (4.6). For a grid connected system, the total amount of electricity purchased from the grid,  $E_{gp}$ , is expressed as,

$$E_{gp} = \sum_0^{8760} (P_{gp}(t)) \quad (4.14)$$

For a grid connected system, the total price of electricity purchased from the grid,  $C_{gp}$ , can be calculated as,

$$C_{gp} = E_{gp} C_g^p \quad (4.15)$$

where,  $C_g^p$  is the unit cost of electricity ( $\$/kWh$ ) purchased from the grid. For a grid connected system, the total amount of electricity supplied to the grid,  $E_{gs}$ , is expressed as,

$$E_{gs} = \sum_0^{8760} (P_{gs}(t)) \quad (4.16)$$

For a grid connected system, the total price of electricity sold to the grid,  $C_{gs}$ , can be calculated as,

$$C_{gs} = E_{gs} C_g^s \quad (4.17)$$

where,  $C_g^s$  is the unit cost of electricity ( $\$/kWh$ ) sold to the grid.

The major economic parameter which defines cost effectiveness of the proposed hybrid energy system is levelized cost of electricity. Further, the minimization of objective function is subjected to following constraints

$$1 \leq N_{sol} \leq N_{sol}^{max} \quad (4.18)$$

$$1 \leq P_{bg} \leq P_{bg}^{max} \quad (4.19)$$

$$P_{gp} \leq P_{gp}^{max} \quad (4.20)$$

$$P_{gs} \leq P_{gs}^{max} \quad (4.21)$$

where,  $N_{sol}^{max}$  is the maximum number of solar PV panels,  $P_{bg}^{max}$  is the maximum rating of biomass gasifier,  $P_{gp}^{max}$  is the maximum grid purchase capacity and  $P_{gs}^{max}$  is the maximum grid sale capacity.

### 4.3.2 Operational strategy

The electricity generated by solar PV panels is kept on first priority over biomass gasifier due to environmental issues. The following operational strategy is opted for the power management of the proposed grid connected hybrid system.

- If the power from solar PV panels  $\{P_{PV}(t) \geq P_L(t)/\eta_{inv}\}$  is adequate and greater than load demand then load can be directly served by solar power and the remaining power

can be sold to the grid and can be calculated as,

$$P_{gs}(t) = \{P_{PV}(t)\eta_{inv} - P_L(t)\} \quad (4.22)$$

- If the  $P_{gs}(t)$  is greater than  $P_{gs}^{max}$  (maximum grid sales capacity) then excess power is dumped and it can be calculated as,

$$P_d(t) = \{P_{PV}(t)\eta_{inv}\} - P_L(t) - P_{gp}^{max} \quad (4.23)$$

- If the power from solar PV panels is not adequate and  $P_L(t) \leq P_{gp}^{max}$  then load can be directly served by the grid power.
- If the power from solar PV panels is not adequate and  $P_L(t) \geq P_{gp}^{max}$  then biomass gasifier is started and load can be served by biomass gasifier, grid and solar power.
- If  $\{P_{PV}(t)\eta_{inv} + P_{bg}(t)\} \geq P_L(t)$  then the remaining power can be sold to the grid within maximum limit of grid sale capacity.

### 4.3.3 Artificial bee colony algorithm

The main steps of the implementation of the ABC algorithm to solve the optimization problem for the above mentioned hybrid system are described as follows,

1. The first step of optimization procedures is the input of annual data of the solar radiation and load demand. Initialize the control parameters of the ABC algorithm, i.e. max cycle number, colony size, population of food sources, dimension of the problem and limit.
2. Consider the number of food sources equals the half of the colony size. For this problem, the colony size is considered 20, so the initial solutions (food sources) are 10 (half of the colony size). The number of parameters to be optimized are 2 (numbers of solar PV panels and size of the biomass gasifier system).
3. Generate a randomly distributed population within the range of boundaries of the parameters (Eq. (4.18) and Eq. (4.19)) by using the following equation

$$P_{ij} = P_j^{min} + rand(0, 1)(P_j^{max} - P_j^{min}) \quad (4.24)$$

where,  $i = 1, 2, 3 \dots SN$ , here,  $SN$  denotes the size of the population and  $j = 1, 2, 3 \dots D$ , whereas,  $D$  is the dimension of the problem or number of optimization parameter.

4. Set trial counters (to store the number of solution trials) to zero.
5. According to initial guess solutions (number of solar PV panels, size of biomass gasifier) perform the following steps.
  - Obtain the solar PV panels output by using Eq. (2.20).
  - According to the solar PV panels and biomass gasifier power output, obtain the grid purchase and sale powers by using Eq. (4.15) and Eq. (4.17). Further, obtain the price of the exchange energy by using Eq. (4.4) and Eq. (4.5).
  - Obtain the annualized cost of sizing components by using Eq. (4.3.1) to Eq. (4.13) for initial population of food sources.
6. The objective function as described in Eq. (4.6) is evaluated for initial food source.
7. Cycle = 1.
8. **Repeat.**
9. Produced a new modified food location for the employed bees by using the following equation
 
$$P_{ij}^{new} = P_{ij} + \phi_{ij}(P_{ij} - P_{kj}) \quad (4.25)$$

where,  $k = 1, 2, 3 \dots SN$  is a randomly chosen index,  $j = 1, 2, 3 \dots D$  is randomly chosen index,  $k$  has to be different from  $j$ . Whereas,  $\phi_{ij}$  is the random integer between the range of  $[-1, 1]$ .
10. If a parameter generated exceeds its predetermined limits, it can be set to an acceptable boundary.
11. Evaluate the objective function described in Eq. (4.6) using new solutions by following the procedure mentioned in step 5.
12. Apply the greedy selection process for the employed bees.

13. Calculate the probability value,  $p_i$ , for the solutions using fitness value by following equation

$$p_i = \frac{fit_i}{\sum_0^{SN} fit_i} \quad (4.26)$$

where,  $fit_i$  is the fitness value corresponding to  $i^{th}$  solution.

14. Produce the new solutions  $P_{ij}^{new}$  by using Eq. (4.25) for the onlookers bees from the solutions selected depending upon the value of  $p_i$ .
15. Evaluate the objective function described in Eq. (4.6) using new solutions by following the procedure mentioned in step 5.
16. Apply the greedy selection process for the onlookers bees.
17. Determine the abandoned solution for the scout, if exists and replace it with a new randomly produced solution.
18. Memorize the best solution obtained as of now.
19. Cycle = Cycle + 1.
20. **Until** (Cycle =  $Maxcycle$ ).

## 4.4 Resource data and component selection

A case study of a small typical village located at a coordinate of 30°26'N latitude and 76°12'E longitudes near Patiala, India is presented in this work. The average daily electrical demands of this village (both summer and winter) are depicted in Figure 2.3. The solar resource data for this location is taken from the NASA surface meteorology website. It is found that average solar radiation for this location is 5.14 kWh/m<sup>2</sup>/day. It is estimated that approximately 1.3-1.5 kg of biomass is required to produce 1 kWh of electricity. The price of biomass in the region is approximately 0.025 \$/kg, which mainly includes transportation and labor charges. This case study is modeled assuming a lifespan of 20 years while the annual interest rate is considered to be 6%. The rate of electricity purchased from the utility grid in the state is 0.1 \$/kWh. The selling price of electricity to the grid is assumed to be 0.15 \$/kWh. The maximum grid purchase and sale power capacity considered are 5 kW and 50 kW respectively. The sensitivity

analysis is carried out for different grid sale capacities of 20, 25, 30, 35, 40, 45 and 50 kW.

Table 4.1 demonstrates different costs of the components used for the work.

Table 4.1: Component costs used in proposed study

Component	Initial cost (per kW)	Replacement cost (per kW)	Maintenance cost (per kW)	lifetime
Photovoltaic module	1200 \$	1200 \$	4 \$/yr	20 yr
Biomass gasifier	1834 \$	1834 \$	0.30 \$/hr upto 20 kW and 0.50 \$/hr above 20 kW	15000 hours
Inverter	127 \$	127 \$	1.34 \$/yr	15 yr
Diesel generator	278 \$	278 \$	0.020 \$/hr	15000 hours

## 4.5 Results and discussions

The ABC algorithm is simulated using MATLAB 2014a program. A simulation is run for one year data with an interval of one hour to examine the behavior of power exchange in different constellations. In the proposed study, the results obtained by HOMER software have been considered for reference and comparison. The control parameters of the ABC algorithm are considered as shown in Table 2.2. Two types of configurations, i.e. stand-alone and grid connected system have been analyzed for cost comparison.

### 4.5.1 Standalone system

Firstly, stand-alone system comprises of solar PV panels and biomass gasifier system have been analyzed by using HOMER and the ABC algorithm. To design the stand-alone system size of inverter,  $P_{inv}$ , is selected according to the peak load demand,  $P_L^{max}(t)$ , during daytime. The minimum load ratio for biomass gasifier and diesel generator is considered as 30%. The following two scenarios of stand-alone hybrid system have been considered in this work (i) Scenario A (without back-up ) (ii) Scenario B (with back-up)

**Scenario A (without back-up)**

In this scenario, the hybrid system is designed to meet all electrical load requirements by renewable energy sources only. No storage or back-up or grid connectivity is considered for the study. [Table 4.2](#) shows the overall optimal results of a stand-alone hybrid system without any storage or grid connectivity for this case study. The case I is generated by using HOMER and case II is obtained by the ABC algorithm. All cases are a feasible solution to meet electrical load. The CRF is found to be 0.08714 for this system for a life span of 20 years and an interest rate of 6% by using Eq. (2.15). NPC of the total system is calculated using CRF and ASC. [Figure 4.2](#) depicts the electricity production of the stand-alone hybrid system. It can be seen from the [Figure 4.2](#) that case I does not satisfy total electricity demand. A total of 131  $kWh/yr$  electricity demand is not satisfied with this configuration. It is also observed that the ABC algorithm proved better results as compared to HOMER. As one can note from [Figure 4.2](#) that the stand-alone system without any storage and grid connectivity dumps huge amounts of electricity.

**Scenario B (with back-up)**

In case of scenario A of stand-alone system, the biggest challenge is the reliability of power to the consumer. If one of the renewable energy sources (particularly biomass) goes off, the total system collapse. To overcome this shortcoming and enhance the reliability of the stand-alone system, a 48  $kW$  diesel generator is included in the configuration. The current diesel price of 0.8\$/L is considered. The diesel generator prioritized in the last due to harmful gas emissions. [Table 4.2](#) demonstrates the overall optimal results of a stand-alone hybrid system with diesel generator for this case study. The inclusion of diesel generator improves the reliability of the system while the pollutant emissions as compared to scenario A are increased. The inclusion of diesel generator increases the NPC of the system which result high LCOE of the system. [Figure 4.3](#) shows the convergence characteristic of the ABC algorithm for the stand-alone hybrid energy system for both cases. From these simulation results, it can be summarized that from the proposed stand-alone system the LCOE obtained in all cases is more as compared to the existing grid purchase cost (0.1\$/ $kWh$ ). This stand-alone system may be a suitable choice of reliable electricity in the case of a remote or off grid location where LCOE is not a great concern.

Table 4.2: Optimal sizing result for stand-alone hybrid PV-biomass energy system

		Algorithm	PV (Units)	Biomass gasifier (kW)	DG (kW)	Inverter (kW)	Gasifier running (hours)	DG running (hours)	ASC (\$/yr)	NPC (\$)	LCOE (\$/kWh)
Scenario A(Without back-up)	CASE I	HOMER	76	47	-	37	5,687	-	53,141	609,524	0.349
	CASE II	ABC	72	48	-	37	5,047	-	47,388	543,814	0.310
Scenario B (With back-up)	CASE I	HOMER	76	47	48	37	5,381	306	55,780	639,796	0.366
	CASE II	ABC	72	48	48	37	5,759	-	54,891	629,592	0.360

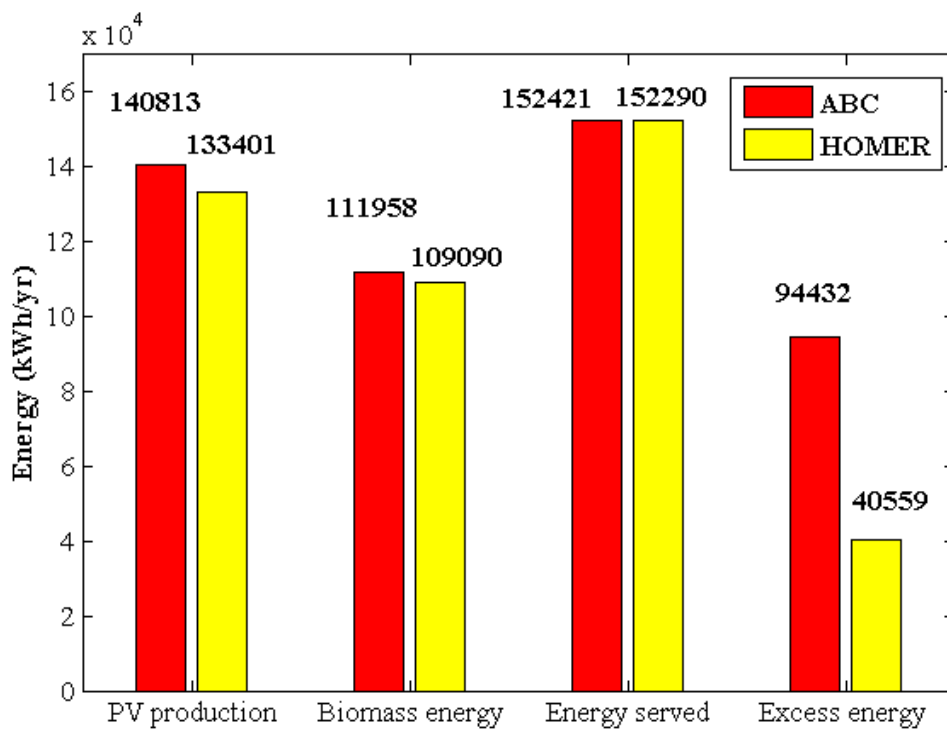


Figure 4.2: Energy produced by the stand-alone hybrid PV-biomass energy system (scenario A).

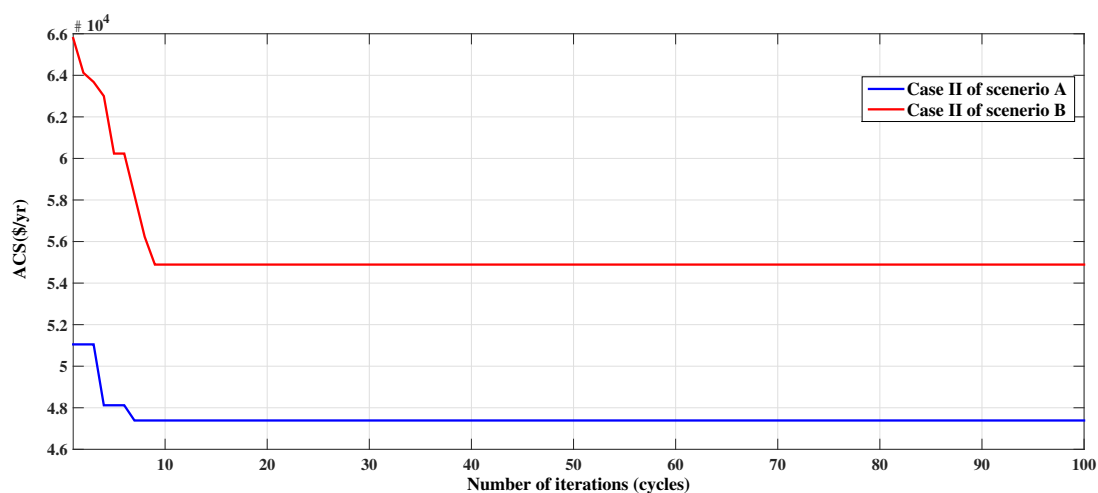


Figure 4.3: Convergence characteristic of the ABC algorithm for the stand-alone system

## 4.5.2 Grid connected system

The biggest drawbacks in the case of aforementioned stand-alone system are relatively high LCOE and the intermittent nature of generating power due to high dependency on weather conditions. Table 4.3 shows the complete optimization results obtained by HOMER and ABC algorithm for grid connected hybrid PV-biomass system as shown in Figure 4.1. The major drawback with cases I and II (Table 4.3) is excess or dump energy. These two cases were obtained with the priority of LCOE to be minimized. Further, the simulation is carried out for the third case with the main objective of meeting the load demand and minimizing the excess energy. The excess energy which is given to dump load can be minimized by the optimization algorithm by imposing a high penalty on excess energy in the objective function. This system sales less electricity to the grid as compared to case I and case II therefore the LCOE is high. Figure 4.4 depicts the convergence characteristics of the applied ABC algorithm for the case II and III. It has been observed that after almost 10 iterations, the optimization algorithm converges completely and provide optimal solutions.

Table 4.3: Optimal sizing result for grid connected hybrid PV-biomass energy system

S.No.	Algorithm	PV	Biomass gasifier	Inverter	Grid sale capacity	Grid purchase capacity	Biomass running	ASC	NPC	LCOE
		(Units)	(kW)	(kW)	(kW)	(kW)	(hours)	(\$/yr)	(\$)	(\$/kWh)
CASE I	HOMER	100	45	85	50	5	5,012	17,916	205,499	0.118
CASE II	ABC	128	43	88	50	5	4,915	16,748	192,162	0.110
CASE III	ABC	73	43	88	50	5	5,316	21,655	248,014	0.141

Table 4.4 shows a brief comparison of electricity generation and consumption for grid connected system suggested by HOMER and the ABC algorithm for all three cases. For further discussion the case II of Table 4.3 is opted as an optimal configuration for this case study. Figure 4.5 illustrates the detailed monthly electricity production for the system in the case II of Table 4.3. It is observed that the energy sold to the grid is more as compared to energy purchased from the grid. This hybrid system purchase electricity from grid mainly in the summer when electrical load is more. Table 4.5 shows the complete annualized cost analysis for the case II. A complete cash flow summary of the proposed hybrid system during the project lifetime is presented in Figure 4.6. It can be observed from Table 4.5 that biomass gasifier replacement cost has high impact on total ASC of the system. Due to less operational life, the biomass gasifier system replacement cost is high. For configuration in case II of Table

Table 4.4: Electricity production and consumption by HOMER and applied ABC algorithm

Energy production						
	(CASE I)		(CASE II)		(CASE III)	
	<i>kWh/yr</i>	%	<i>kWh/yr</i>	%	<i>kWh/yr</i>	%
PV panels	185,280	45	237,159	52.6	135,050	36.8
Biomass generator	225,540	54.6	211,345	46.9	228,588	62.5
Grid purchases	1,719	0.4	2,085	0.5	2,515	0.7
Total	412,540	100	450,589	100	366,153	100
Energy consumption						
	(CASE I)		(CASE II)		(CASE III)	
	<i>kWh/yr</i>	%	<i>kWh/yr</i>	%	<i>kWh/yr</i>	%
AC load served	152,421	39	152,421	38	152,421	44
Grid sales	234,752	61	247,311	62	194,290	55
Total	387,173	100	399,732	100	346,711	100
Excess electricity	7,598		30,155		0	

Table 4.5: Cost analysis obtained by the ABC algorithm for case II ( Table 5)

Component	Capital	Replacement	Maintenance cost	Fuel	Salvage	Total
	(\$/yr)	(\$/yr)	(\$/yr)	(\$/yr)	(\$/yr)	(\$/yr)
PV	13,392	0	512	0	0	13,904
Biomass	6,876	23,173	2,464	6,892	-958	38,440
Grid	0	0	-36,888	0	0	-36,888
Inverter	972	406	117	0	202	1,293
Total	21,239	23,579	-33,801	6,892	-1,160	16,748

4.3 the total biomass gasifier system running hours are 4,915 in a year, which results 3.05 years operational life of the biomass gasifier system by using Eq. (4.10). Therefore, approximately six replacements are required during the project lifetime.

Figure 4.7 demonstrates the optimal power management of the proposed system (case II of Table 4.3) in order to study the hourly power exchange between PV, biomass and grid. The simulation is conducted for two days where one day in winter and the other day of summer is taken for validation of the scheme. The first part of the Figure 4.7 shows the optimized power management in a typical sunny day of summer. It is observed that in the summer season PV power contribution is more. Second part of the Figure 4.7 illustrates the power management of a typical winter cloudy day, it has been observed that even during overcast of the cloud, the proposed system has optimized the generation of the biomass and grid purchased power. In the cases of outage conditions (grid failure), the system behaves in stand-alone (with back-up) mode.

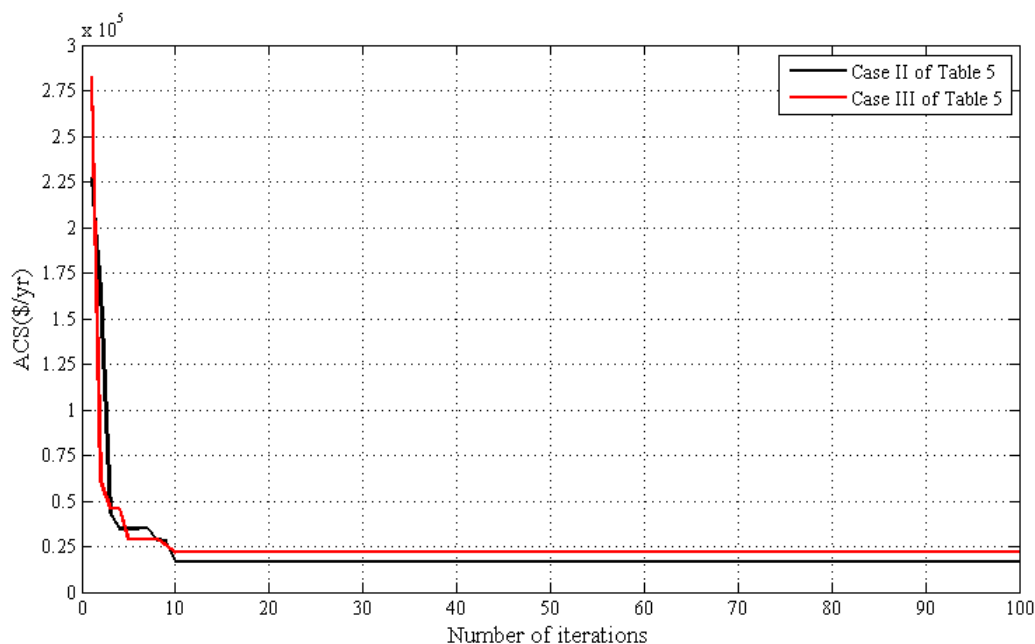


Figure 4.4: Convergence characteristics of the ABC algorithm for grid connected system (case II and III of Table 4.3)

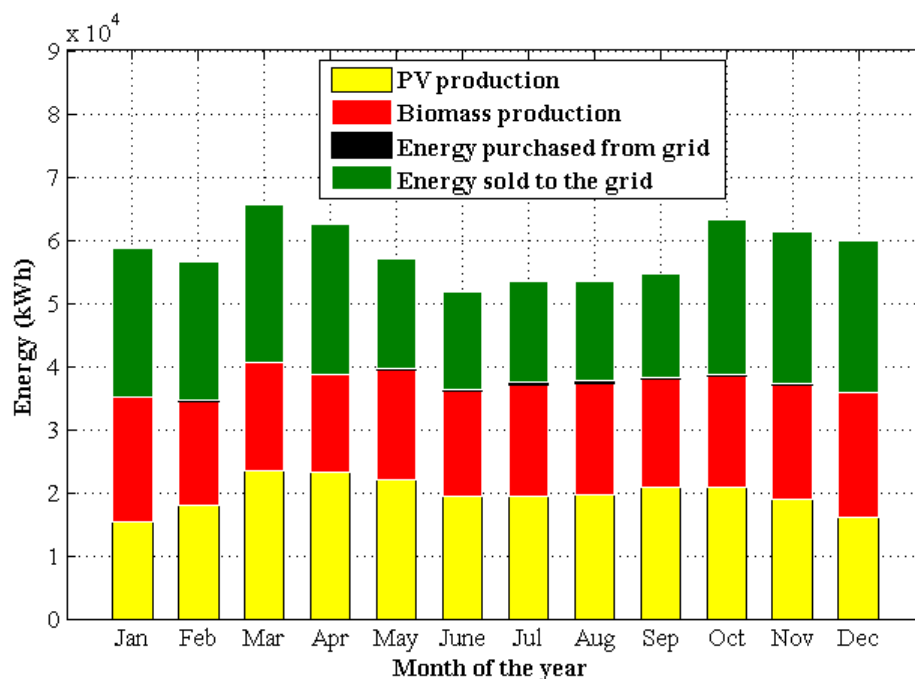


Figure 4.5: Monthly average electricity production during one year for case II (Table 4.3)

In the sensitivity analysis, one major parameter such as grid sale capacity has been considered in this study. Figure 4.8 illustrates the effect of grid sale capacity on annual PV power generation, biomass power generation, LCOE and electricity sold to the grid. It can be seen from the Figure 4.8 that as grid sale capacity increases the contribution of PV and biomass

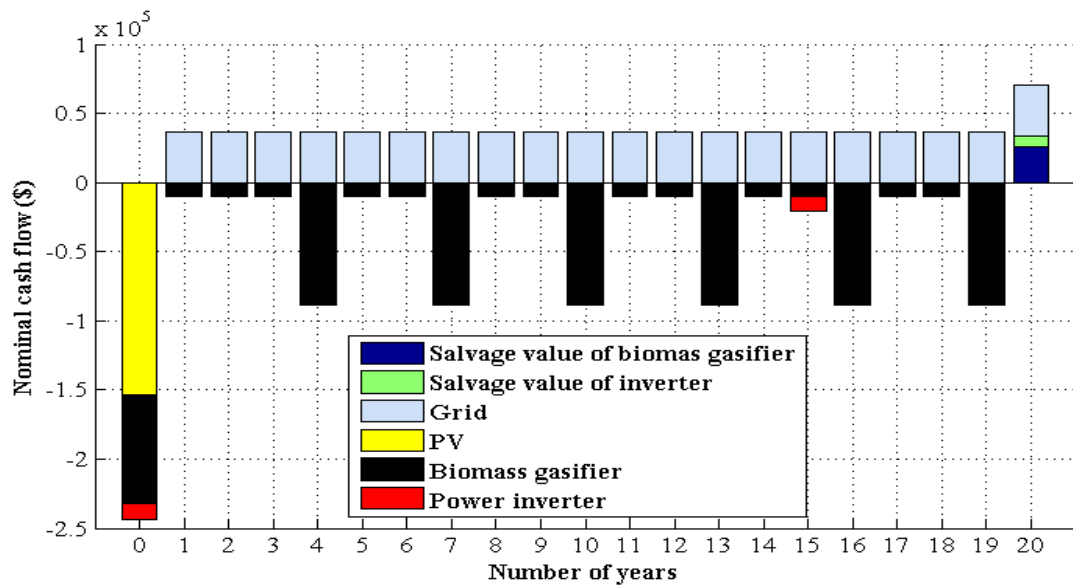


Figure 4.6: Nominal cash flow during the project lifetime for case II (Table 4.3)

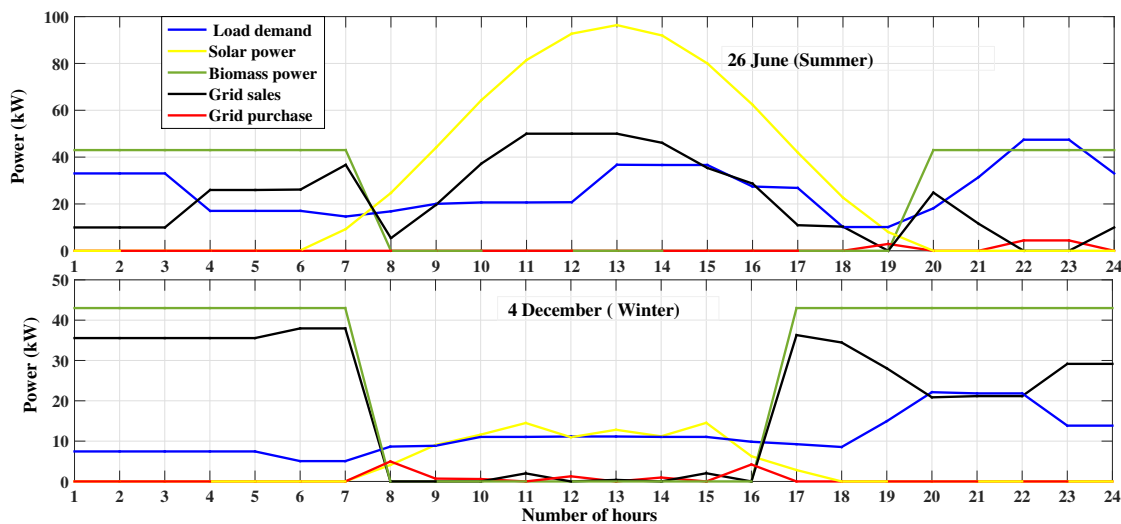


Figure 4.7: Power management indicating load demand, biomass, solar, grid sales and purchased powers in the case II (Table 4.3)

power generation increases almost linearly. Moreover, after 40 kW of grid sale capacity, the biomass power contribution decrease and utilization of solar power increases. It is found that if grid sale capacity increases, the LCOE decreases. It can also be observed from the [Figure 4.8](#) that LCOE of the system is minimum when grid sale capacity is maximum. LCOE is highly dependent on grid sale capacity. The main findings of the chapter can be summarized as,

- For a stand-alone PV-biomass system the LCOE is found to be 0.349 \$/kWh, while for a grid connected PV-biomass system LCOE is obtained to be 0.110 \$/kWh by the ABC

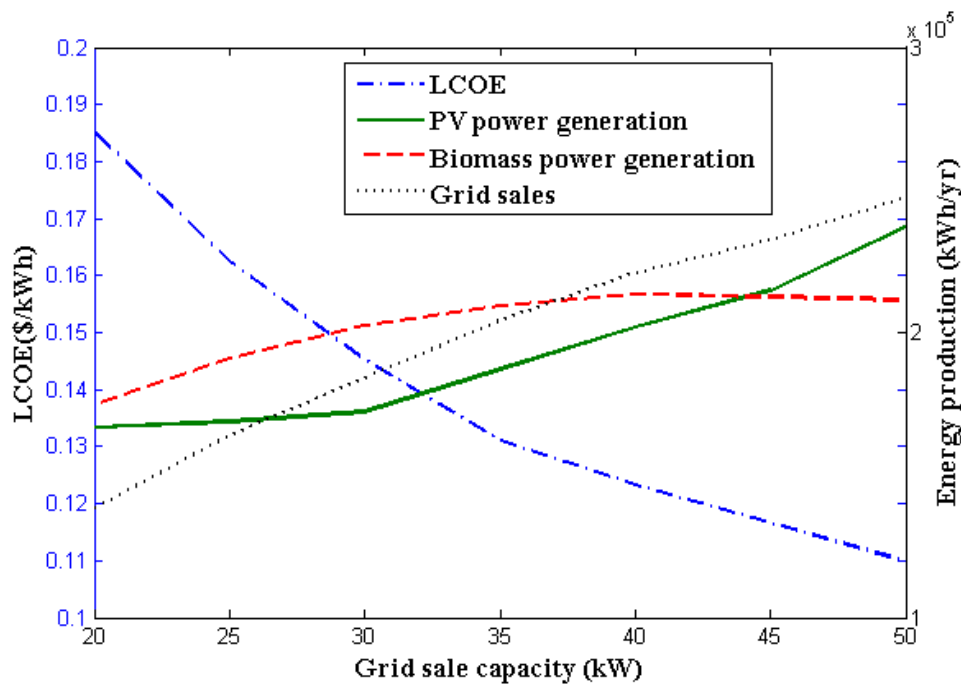


Figure 4.8: Effect of grid sale capacity on PV production, biomass power, grid sales and LCOE for case II (Table 4.3)

algorithm (Table 4.2 and Table 4.3).

- A total of 2,085  $kWh/yr$  energy is purchased from the grid and 247,311  $kWh/yr$  energy is sold back to the grid in the grid connected system (Table 4.4).
- A total of 276 tons of biomass feedstock has been utilized for power generation in the grid connected system (Table 4.3).
- Effect of grid sale capacity has been investigated on LCOE of the system and it is observed that LCOE decreases as grid sale capacity increases (Figure 4.8).
- As compared to the stand-alone system, the grid connected system can achieve a higher power supply reliability.
- The applied ABC algorithm reduces hours of calculation time as compared to HOMER to few minutes.

## 4.6 Conclusion

This chapter explored a methodology for optimal sizing of a grid connected PV-biomass hybrid energy system using the ABC algorithm and HOMER. First, a mathematical model of hybrid system was presented. Then optimization algorithm and operational strategy were explained. Finally, the optimal sizing method was applied to find out the optimal configuration in case of stand-alone and grid connected PV-biomass hybrid system. The results obtained clearly show that grid connected hybrid system may be a cost effective electrification solution for numerous villages in developing countries. It is also perceived from the obtained results that grid connected PV-biomass system shows better results in terms of cost effectiveness and reliability as compared to stand-alone PV-biomass system.

## Chapter 5

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# HYBRID SYSTEM WITH DISTRIBUTED ENERGY STORAGE

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### 5.1 Introduction

In recent years, renewable energy sources based Micro-grids have become an alternative to fossil fuels to fulfill energy demands of isolated communities. A MG consists of distributed energy sources, a cluster of controllable loads and storage devices. There are different types of distributed energy storage system (DESS) available that could be used in MGs such as batteries, plug in hybrid vehicle (PHEV) batteries, super-capacitors and flywheels. A significant research growth has been observed in integration of distributed energy sources and DESS into the MG. The output power of different RESs and DESS needs to be controlled and coordinated to enhance the reliability of the MG. As the DESS and RESs are integrated in the MG, the need for real time power management commences and needs further attention. In order to optimize power management between different components of MG, several researches have been carried out.

[Ribeiro \*et al.\* \(2011\)](#) proposed a standalone MG which was based on hybrid wind-solar-batteries to meet the electricity demand of an isolated island in Brazil. In this work, the authors implemented a SCADA system to control the power flow between different components of the MG. [Xu and Chen \(2011\)](#) developed operation and control strategy of a DC microgrid, consisting a wind turbine, a battery energy storage system and DC load. The authors addressed different issues associated with the integration of MG with the main utility grid. [Olivares \*et al.\* \(2011\)](#) formulated a three phase mathematical model of an isolated MG to address the voltage fluctuations using reactive support. [Salmasi and Hosseinzadeh \(2015\)](#) proposed a fuzzy based controller to manage the battery bank in an isolated hybrid AC/DC microgrid. In case of a

stand-alone MG, large battery banks are used to store energy and feed the stored electricity back into the MG. Due to the intermittent nature of RESs, the battery bank with a fast response is required to manage the power. To achieve this, ultra-capacitors have been introduced as a storage device along with a battery bank. [Zhou and François \(2011\)](#) introduced the concept of a composite energy storage system which consists of high energy density storage battery as well as high power ultra-capacitors. [Tani \*et al.\* \(2015\)](#) suggested that power fluctuations due to the intermittent nature of wind energy and load could be compensated with the use of ultra-capacitors in decentralized generation system based on renewable energy.

Generally, a MG consists of large battery banks or ultra-capacitors as a storage device. However, a replacement to these battery banks can be provided by batteries of Electric vehicles (EVs) or PHEVs [[Tan \*et al.\* \(2013b\)](#)]. The energy stored in the batteries of PHEVs can be used by the MG during peak or energy-deficient hours. [Pahasa and Ngamroo \(2015\)](#) proposed a multiple model predictive control for management of PHEV batteries in a MG. Although the suggested scheme increased MG's performance with respect to frequency stabilizations, the authors did not discuss the effect of regulating batteries's power on voltage of the system. [Chen and Duan \(2014\)](#) proposed a method based on genetic algorithm for optimal integration of PHEVs into MGs. In this work, the authors have considered the optimal number of parking by the proper scheduling of PHEVs in the MG. In a similar work, [Su \*et al.\* \(2014\)](#) investigated energy scheduling to address the challenges associated with the intermittent nature of RESs, PHEVs and battery banks. [Kam and Sark \(2015\)](#) proposed a model of lower voltage MG which consists of batteries of EVs and have used these as a DESS. In this work, the authors have presented a linear programming based algorithm to manage the charging profile of multiple EVs in real-time. The economic analysis and operational strategy of integration of DESS along with solar PV in commercial buildings (considered as a small MG) have been investigated by [Roy \*et al.\* \(2014\)](#) and [Liu \*et al.\* \(2015\)](#). [Zhang and Chen \(2014\)](#) proposed a price incentive model based on fuzzy control technique to utilize EVs with battery swapping stations for optimal cost and maximum profit of an isolated MG.

It is expected that millions of DESS can be integrated into the existing power system in near future [[Kempton and Tomić \(2005\)](#)]. Integration of DESS along with RESs will provide a cost effective, energy efficient and secure solution to the MG. Charging and discharging capabilities of DESS have a significant role in power management. Whereas, the uncoordinated

charging and discharging of DESS can arise some serious issues such as high power losses, increased fault levels, voltage deviations and some other power quality issues [Pahasa and Ngamroo (2015)]. Allowing the DESS to charge and discharge without any control scheme may lead to power fluctuations in the MG. Thus, a framework for better energy management is required to coordinate the charging and discharging rate of batteries in MG.

Large scale integration of DESS into MG requires efficient charging and discharging mechanisms to coordinate with the different components of the MGs. Charging stations (CSs) will play an important role in proper coordination of DESS. Recently, several conventional and artificial intelligence techniques have been reported in literature for the same. Das *et al.* (2014) investigated a simple mathematical model to integrate EVs into grid based on different charging and discharging rate of batteries. Singh (2013) proposed a model of a multi-CS for batteries of EVs using fuzzy based controller to control the charging and discharging rate of batteries in the distribution network. Matos *et al.* (2013) proposed a control strategy to control the SOC of the battery bank with the help of limiting the power generated by the RESs. Several studies have been carried out to control and optimize the DESS for voltage support using droop control method.

Li and Wang (2008) proposed a coordinated control of the diesel generators and battery storage system in MG based on the conventional droop control method. In this work, the authors considered power fluctuations in MG mainly due to load variations. In a different approach, Wu *et al.* (2013) suggested a stochastic framework for efficient integration of PHEVs in a MG integrated with wind power generation. However, the authors did not discuss the efficacy of the control scheme for a hybrid MG system. Kakigano *et al.* (2013) presented a voltage control mechanism that combines fuzzy control with gain-scheduling techniques for power sharing and energy management in order to balance the SOC and output power of each energy storage unit. However, the authors have not considered the effect of fast charging and discharging of energy storage units. Bevrani and Shokoohi (2013) proposed an intelligent droop control for voltage and frequency regulation simultaneously in an islanded MG. The authors developed an adaptive neuro-fuzzy inference system to simulate dynamic behavior of the generalized droop control. Lu *et al.* (2014) presented the coordinated control of DESS in DC microgrid. In this work, the authors balanced the SOC of each energy storage unit by applying the adaptive droop control method. In another work, Lu *et al.* (2015) proposed double-quadrant SOC based droop

control method for DESS for power distribution in autonomous MG.

The aforementioned discussions infer that considerable work has been done on optimal power management of batteries in MGs integrated with RESs. However, incorporation of DESS for MG stabilization has not gained much attention of the researchers. In current literature, power scheduling of RESs using DESS for reliable operation of MGs with respect to the voltage of the system is not discussed. Also, most of the work found in literature regarding power flow management in MGs through DESS has not considered individual battery needs, such as SOC limits and charging/discharging rates. Further, charging and discharging efficiency are assumed same for varying charging/discharging rates. Considering the above mentioned issues, this chapter proposes a novel power scheduling control scheme for secure and sustainable operation of MG integrated with DESS and RESs. Three different RESs, i.e., solar, wind and FC has been introduced in an isolated MG. Instead of using a single large energy storage, the proposed work considers DESS which is going to be a future EVs or other composite energy storage to support the MG. To share the power among the DESS, P/V droop controller has been used. To manage the charging and discharging of DESS, three CSs are placed at three different locations. The sharing of power among the batteries is based on voltage droop received on the MG bus. The proposed work meets the following objectives.

- A novel power optimization methodology for ensuring a reliable and stable operation in an islanded MG integrated with RESs, DESS and CSs.
- Effective employment of voltage droop controller for optimal distribution of power among CSs, to enhance voltage profile of MG and simultaneously satisfy charging requirements of CSs.
- Proper distribution of power among each DESS, such that they act as energy sources and loads, according to the power needs of the MG.
- Adequate regulation of charging and discharging rates of batteries at CSs, to ensure a stable operation of the system during events, such as failure of any generation source.

## 5.2 Modelling of the system

In this work, the proposed MG consists of three different RESs (solar, wind and FC), DG, electrical loads and three CSs. For effective integration of DESS into a MG, a CS is required to coordinate charging and discharging of the individual batteries. Batteries present at any CS will charge and discharge based on MG command. Different types of batteries can be handled at the CSs for power support while maintaining stability of the MG. The amount of power which has to be exchanged by the batteries will be decided based on voltage droop. The purpose of using the voltage droop is to distribute the power among different batteries present at any CS. Figure 5.1 shows the complete system architecture of a typical MG in grid connected mode depicting all components. The modeling of different components is discussed as follows.

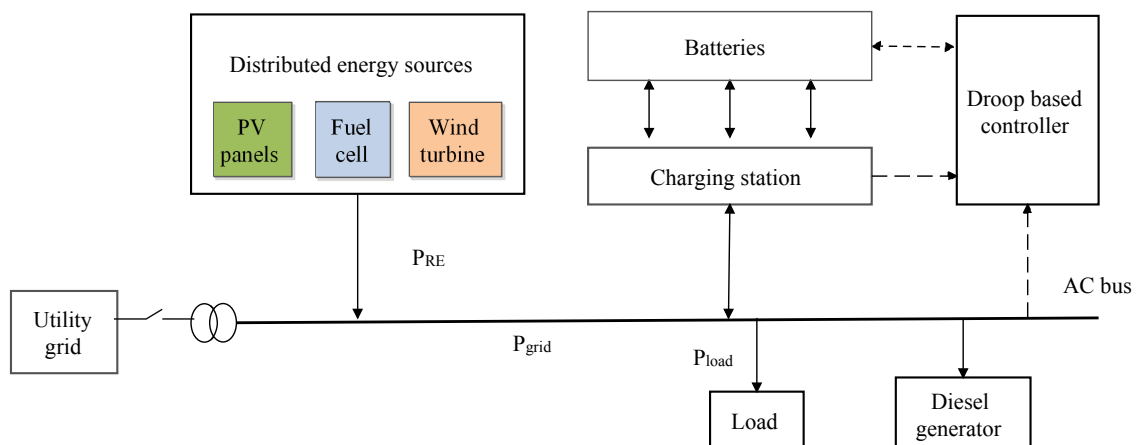


Figure 5.1: Proposed MG system with RES, DESS and charging station

### 5.2.1 Fuel cells

FCs are electrochemical devices that convert the chemical energy of a fuel directly into electrical energy. FCs are becoming popular because of their high generation efficiency, power density, zero pollution, high reliability and durability. The FCs provide continuous 24 hour power supply to the system. The advantage of using FCs is that it uses non hydrocarbon fuel to produce clean power, with hydrogen fuel generated on site using electrolyzer. Proton exchange membrane FC is used in proposed model due to its reliability and availability in large industrial scale capacities.

### 5.2.2 Distributed energy storage systems

As the number of DESS is increasing in the existing power system, the energy management of any MG is becoming a critical issue. In case of DESS, the major component is storage batteries. The excess energy at MG is stored in the DESS, and is delivered back during low power generation in system. Therefore, the successful implementation of the MG depends largely on the storage devices. There are various types of batteries available such as lithium-ion, lead acid and nickel hydride etc. The charging rate of the batteries is also monitored and maintained within the specified limits. In this study, six different types of batteries of different ratings have been considered and are shown in [Table 5.1](#).

The rest of the components such as solar photovoltaic and wind turbine power have been modeled as already discussed in subsection [2.2.1](#) and [2.2.2](#), respectively.

Table 5.1: Battery specifications

Battery rating	Voltage	Ahr	Nominal usable capacity	$C_{rate} D_{rate}$	Max. charging current
16 kWh	200	80	12.8	2	4
20 kWh	200	100	16	2	5
24 kWh	200	120	19.2	2	6
30 kWh	200	150	24	2	7.5
40 kWh	200	200	32	2	10
50 kWh	200	250	40	2	12.5

## 5.3 Problem formulation

A complete schematic diagram of the proposed MG system is demonstrated in [Figure 5.2](#). The MG is connected to the utility grid through the switch as depicted in the figure. Three types of RESs (solar, wind and FC) and a DG have been considered in the MG for power generation. Three different types of loads namely residential, commercial and industrial have been considered. To enhanced reliability of supply at load end, batteries are installed in the suggested MG. For proper sharing of the power among the batteries, three CSs have been integrated at different places in MG. First CS is near residential load, the second one is near the commercial load and third CS is installed near the industrial load. On a particular CS, six different types of batteries have been considered. For optimal control of charging and

discharging of batteries, a droop based intelligent controller has been proposed. To coordinate the power flow between the different CSs, an aggregator (AG) is proposed. In the following subsections, MG operation, droop based controller and finally distribution of power among the batteries are discussed.

### 5.3.1 MG operation

The electricity generated by RESs is kept on first priority over DG power due to environmental issues. The following generalized operational strategy is opted for the optimal power management of the proposed MG.

- The total power generated by RESs at any time  $t$  is defined as  $P_{RE}(t)$  and it can be given as,

$$P_{RE}(t) = \{P_{sol}(t) + P_{wt}(t) + P_{fc}(t)\} \quad (5.1)$$

where,  $P_{sol}(t)$  is the total power generated by solar PV panels,  $P_{wt}(t)$  is the total power generated by wind turbines and  $P_{fc}(t)$  is the power generated by FCs.

- The total electrical load demand at any time  $t$  is defined as  $P_{load}(t)$  and it is given as,

$$P_{load}(t) = \{P_{load}^r(t) + P_{load}^c(t) + P_{load}^i(t)\} \quad (5.2)$$

where,  $P_{load}^r(t)$  is the residential load,  $P_{load}^c(t)$  is the commercial load and  $P_{load}^i(t)$  is the industrial load.

- If the power generated by RESs is adequate and greater than load demand  $\{P_{RE}(t)\} \geq \{P_{load}(t)\}$ , then the load can be directly served by RESs and the remaining power can be supplied to CS, and given as

$$P^{CS}(t) = \{P_{RE}(t)\} - \{P_{load}(t)\} \quad (5.3)$$

- If the power generated by RESs is not adequate  $\{P_{RE}(t)\} < \{P_{load}(t)\}$ , then remaining power can be served by the CSs as given by Eq. (5.3)
- If the total power supplied by CSs and RESs  $\{P^{CS}(t) + P_{RE}(t)\} < \{P_{load}(t)\}$  are unable to satisfy the total load, then the remaining power,  $P_{dg}(t)$ , can be supplied by the DG and

given as,

$$P_{dg}(t) = \{P_{load}(t)\} - \{P_{RE}(t) + P^{CS}(t)\} \quad (5.4)$$

### 5.3.2 Voltage control by droop characteristics

Better coordinated control and operation of RESs with batteries will be helpful to mitigate power crisis issues. Moreover, an optimal power management between various generation systems, storage devices and load improves stability of the MG. In this proposed work, voltage droop method is implemented to control power ( $P$ ) as a function of voltage ( $V$ ). Here, active power vs voltage is preferred instead of reactive power vs voltage [Laaksonen *et al.* (2005)].

In grid connected mode, the system frequency is mainly grid controlled. In an islanded MG, which consists of different RESs and DESS, the conventional operation and control strategies can not be applied. In the islanded mode of MG, two main factors which need to be maintained in predefined limits are frequency and voltage. The conventional frequency droop characteristic can be given as,

$$f^* = f_r + m(P_r - P^*) \quad (5.5)$$

where,  $f^*$  is the instantaneous frequency of the corresponding generator considered,  $f_r$  is the reference frequency of the system,  $P_r$  is the desired real power output of the generator and  $P^*$  is the measured actual real power output of the generator. The droop coefficient is denoted by  $m$ . Further, the conventional voltage droop control characteristic can be given by,

$$V^* = V_r + n(Q_r - Q^*) \quad (5.6)$$

where,  $V^*$  is the instantaneous voltage magnitude,  $V_r$  is the reference voltage of the MG,  $Q_r$  is the desired reactive power output of the generator and  $Q^*$  is the measured actual reactive power output. The voltage droop coefficient is denoted by  $n$ . The typical voltage and frequency droop characteristics are shown in Figure 5.3 (a) [Ghosh and Dewadasa].

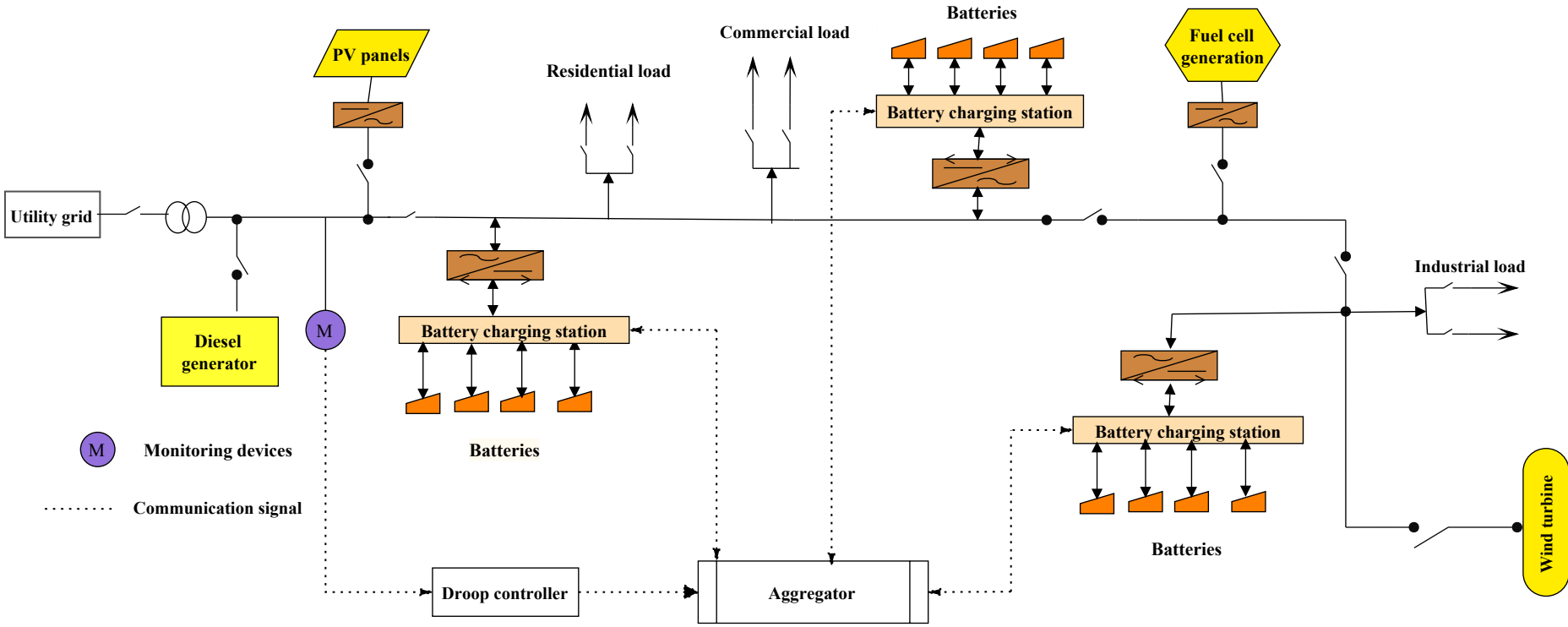


Figure 5.2: Schematic diagram of the proposed microgrid system

In high voltage transmission lines, inductance in the line is much larger than the resistance. However, MG operates at a lower voltage with distribution lines that have high resistances. In the low voltage MG, the voltage profile is related to the active power distribution. Voltage control and the active power dispatch are the major control issues in the MG. Generally in any MG, bus voltage fluctuations occur due to fluctuation produced by solar PV power, wind power and loads. The suppression of this fluctuation is achieved by controllable energy storages connected to the MG. Therefore, in this work batteries are controlled according to the droop characteristics and load is shared according to the capacities of batteries. The active power ( $P$ ) and the reactive power ( $Q$ ) of resistive coupled voltage sources as shown in Figure 5.3 (b) can be calculated as given below [Engler and Soultanis (2005)].

$$Q = \frac{V_1 V_2}{R_{line}} \sin \delta \quad (5.7)$$

$$P = \frac{V_2^2}{R_{line}} - \frac{V_1 V_2}{R_{line}} \cos \delta \quad (5.8)$$

where,  $R_{line}$  is the line resistance. Here, power angle  $\delta$  is assumed to be negligibly small, thus,

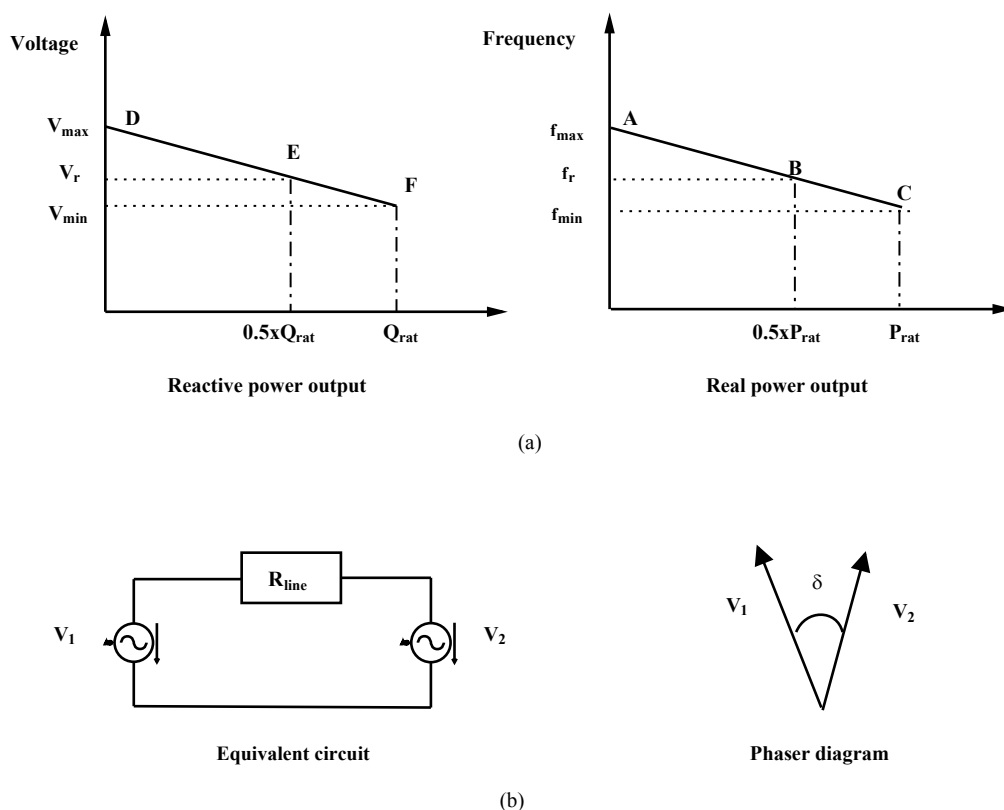


Figure 5.3: (a) Voltage and frequency droop characteristic of a generator (b) Resistive coupled voltage sources

the active power can be illustrated as follows.

$$P = K_v(V_2 - V_1) \quad (5.9)$$

$$K_v = \frac{V_2}{R_{line}} \quad (5.10)$$

As the active power depends upon  $(V_2 - V_1)$ , voltage control through active power compensation is preferred in low voltage distribution networks. Thus, active power/voltage ( $P/V$ ) droop controller is suggested for the considered MG.

### 5.3.3 Division of power based on droop characteristics

In this work, P/V droop control mechanism is used to control the voltage of the MG as well as share the responsibility of power among different DESS which are participating in CS. Initially, the aggregator receives the power signal ( $P_{AG}$ ) from MG. The power regulation signal,  $P_{AG}$ , can be given as

$$P_{AG} = \{P_{RE}(t) + P_{dg}(t)\} - P_{load}(t) \quad (5.11)$$

This power signal is divided among CSs with the help of Droop Based Controller (DBC). The DBC calculates the power set point  $P_i^{ref}$  for each CS using below mentioned equation.

$$P_i^{ref} = P_i^{fact} P_{AG} \quad (5.12)$$

where,  $P_i^{fact}$  is the participation factor of  $i^{th}$  CS. This participation factor can be computed as follows.

$$P_i^{fact} = \frac{E_i^{CS}}{E^{CS}} \quad (5.13)$$

In Eq. (5.13),  $E_i^{CS}$  is the available or required batteries' energy of the  $i^{th}$  CS and  $E^{CS}$  is the total available or required energy in all the CSs. These parameters are computed in Section 5.3.4. Moreover, DBC uses the  $P_i^{ref}$  computed in Eq. (5.12) to manage the voltage at connecting

node. This voltage is managed according to the droop characteristics mentioned below.

$$V = V_{err} + k(P_i + P_i^{ref}) \quad (5.14)$$

where,  $k$  is the droop parameter and  $P_i$  is the instantaneous power measured at individual CS.  $V_{err}$  is the voltage error signal and can be calculated as

$$V_{err} = V_{ref} - V_0 \quad (5.15)$$

The block diagram of the proposed voltage droop controller is depicted in [Figure 5.4](#).

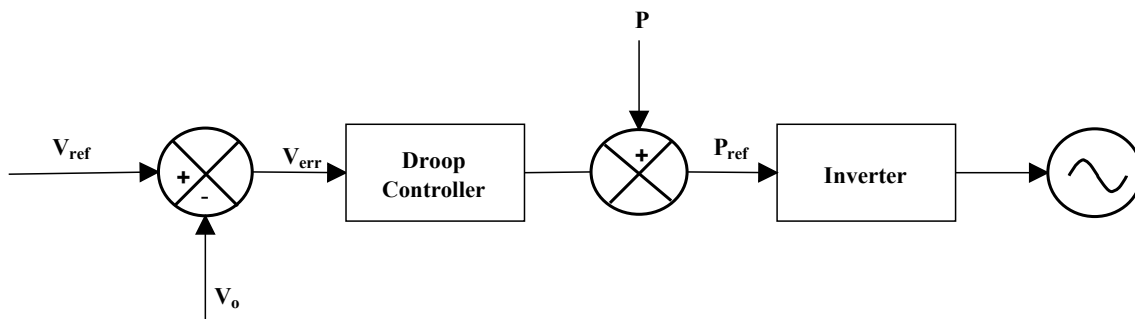


Figure 5.4: Voltage droop controller

### 5.3.4 Battery control algorithm

In this work, three CSs with equal number of batteries have been considered. For an individual battery, when the SOC is less than  $SOC_{min}$ , the battery needs to charge first. However, when the SOC is higher than  $SOC_{min}$  and less than a certain predefined maximum limit called  $SOC_{max}$ , the individual battery shares power with the MG. SOC is a critical parameter for management of battery and determining its energy. The total energy available at any CS is given as,

$$E_i^{CS} = \sum_{j=1}^m E_{ij} \quad (5.16)$$

where,  $m$  is the number of batteries, and  $E_{ij}$  is the energy available in  $j^{th}$  battery of  $i^{th}$  CS.  $E_{ij}$  is calculated as follows.

$$E_{ij} = \frac{SOC_j(t)}{100} V_b Ahr_j \quad (5.17)$$

where,  $SOC_j(t)$  depends on whether energy is available in the battery for discharging or energy is required by the battery for charging.  $Ahr_j$  is the rated ampere hours capacity of  $j^{th}$  battery and  $V_b$  is the battery voltage. The total energy available at all CSs can be given as,

$$E^{CS} = \sum_{i=1}^n E_i^{CS} \quad (5.18)$$

Based on the calculated batteries' energy,  $P_i^{CS}$  can be redistributed to each battery of the  $i^{th}$  CS. The power shared with  $j^{th}$  battery of  $i^{th}$  CS is  $P_{ij}^{CS}$  and can be given as follows.

$$P_{ij}^{CS} = \frac{E_{ij}}{\sum_{i=1}^m E_{ij}} P_i^{CS} \quad (5.19)$$

The  $Ahr$  (rated capacity) of the battery is the total energy that can be discharged from a fully charged battery under specified conditions. Another major factor which has to be controlled is the battery charging rate, i.e.,  $C_{rate}$ , and is given as,

$$C_{rate} = \frac{P_{ij}^{CS}}{V_b Ahr_j} \quad (5.20)$$

If  $P_{ij}^{CS}$  is positive, the battery will get discharged else if,  $P_{ij}^{CS}$  is negative, the battery will be charged.  $P_{ij}^{CS}$  is the other parameter which depends upon SOC of the battery. The charging and discharging rates of individual battery are specified by the manufacturer. The charging rate should not go beyond critical or rated charging rate ( $C_{cr}$ ) of the individual battery. The suggested algorithm prevents charging rate of each battery from exceeding  $C_{cr}$ . If the computed charging rate varies,  $P_{ij}^{CS}$  is calculated as follows.

$$P_{ij}^{CS} = C_{cr} V_b Ahr_j \quad (5.21)$$

The available energy for discharging or charging of batteries depends upon the  $SOC(t)$ . If ( $SOC(t) > SOC_{min}$ ), the energy available for discharging in the  $j^{th}$  battery is given as,

$$E_{ij}^d(t) = Ahr_j \{SOC_j(t) - SOC_{min}\} \frac{V_b}{100} \quad (5.22)$$

If ( $SOC(t) < SOC_{min}$ ), energy is required from MG to charge the batteries. The total energy

required for charging of a particular battery is given as,

$$E_{ij}^c(t) = Ahr_j \{SOC_{min} - SOC_j(t)\} \frac{V_b}{100} \quad (5.23)$$

Time taken for charging or discharging of the battery depends upon the charging or discharging rate as given by Eq. (5.20). If  $m1$  and  $m2$  batteries are in discharging and charging state respectively, the net energy available at any CS at time,  $t$ , can be calculated as follows.

$$E_i^{CS} = \sum_{j=1}^{m1} E_{ij}^d(t) \eta_d - \sum_{j=1}^{m2} E_{ij}^c(t) \eta_c \quad (5.24)$$

where,  $\eta_c$  and  $\eta_d$  are the charging and discharging efficiencies, respectively. Further,  $E_{ij}^d(t)$  and  $E_{ij}^c(t)$  can be calculated as

$$\sum_{j=1}^{m1} E_{ij}^d(t) = \frac{V_b}{100} \left[ \sum_{j=1}^{m1} Ahr_j SOC_j(t) - SOC_{min} \sum_{j=1}^{m1} Ahr_j \right] \quad (5.25)$$

$$\sum_{j=1}^{m2} E_{ij}^c(t) = \frac{V_b}{100} \left[ SOC_{min} \sum_{j=1}^{m2} Ahr_j - \sum_{j=1}^{m2} Ahr_j SOC_j(t) \right] \quad (5.26)$$

The SOC of  $j^{th}$  battery of any  $i^{th}$  CS at any time,  $t$ , after charging or discharging can be given as follows.

$$SOC_j(t) = \begin{cases} \frac{E_{ij}(t) - E_{ij}^d(t)}{Ahr_j V_b} \times 100 & \text{discharging} \\ \frac{E_{ij}(t) + E_{ij}^c(t)}{Ahr_j V_b} \times 100 & \text{charging} \end{cases} \quad (5.27)$$

The steps of proposed methodology is briefed under Algorithm-1. The complete flow chart of the battery's charging and discharging system is demonstrated in Figure 5.5.

## 5.4 Results and discussions

This section deals with the implementation of P/V droop control method for distribution of power among different CSs. The simulations have been carried out for the proposed MG as shown in Figure 5.2. In this work, three CSs have been considered, and each CS has six different types of batteries. However, the proposed scheme is extensible to  $n$  number of CSs. These

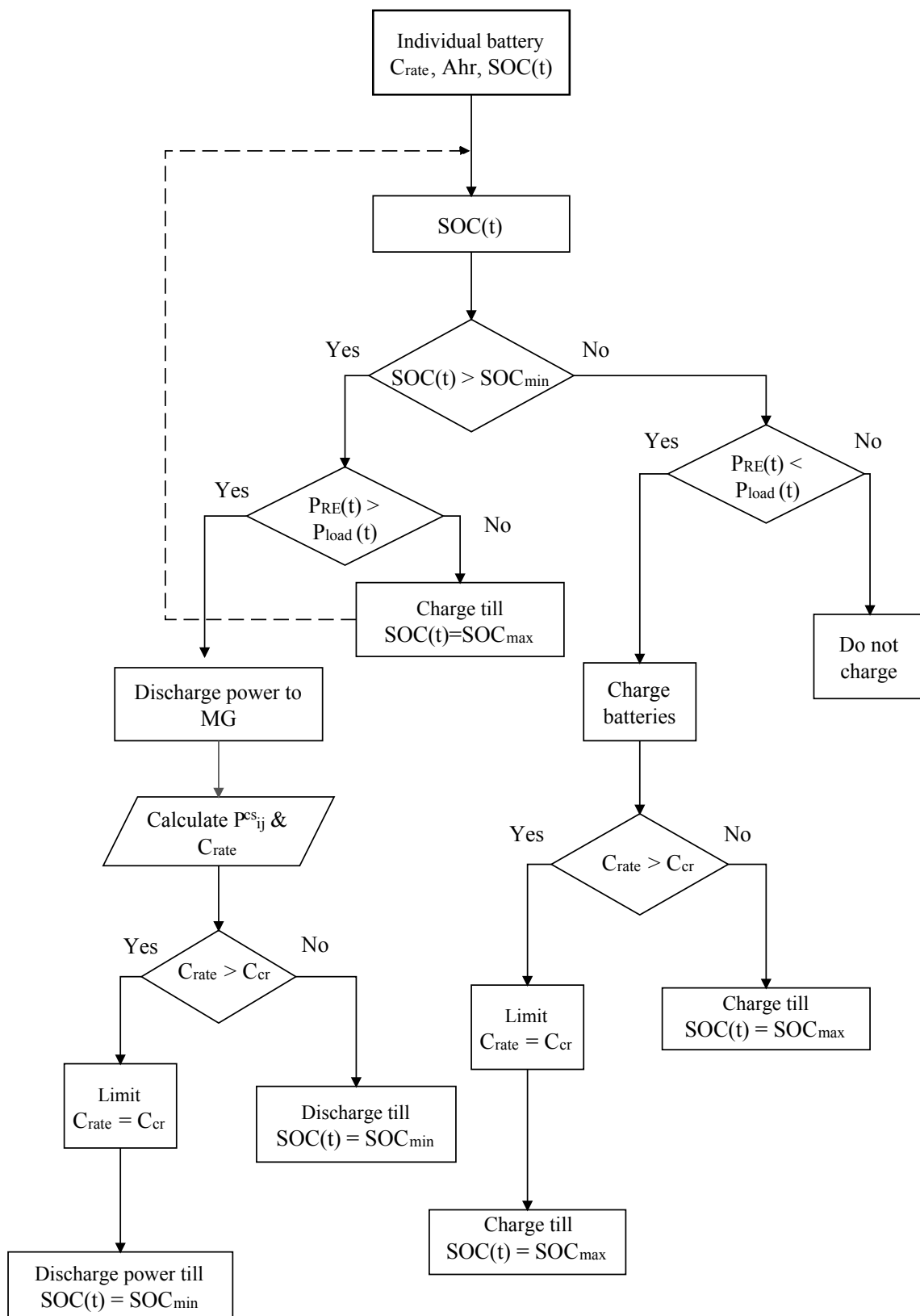


Figure 5.5: Flow chart of the batteries power flow control

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**Algorithm 1**

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**Input:**  $SOC_j(t), P_{AG}, SOC_{min}, P_i, V_o, V_{ref}, k$

**Output:**  $V, E_i^{CS}(t), SOC_j(t)$

- 1: Compute  $E_{ij}$  using (5.17)
  - 2: **if**  $SOC_j(t) > SOC_{min}$  **then**
  - 3:     Compute  $E_{ij}^d(t)$  using (5.22)
  - 4: **else**
  - 5:     Compute  $E_{ij}^c(t)$  using (5.23)
  - 6: **end if**
  - 7: Compute  $E_i^{CS}$  using (5.24)
  - 8: Compute  $P_{ij}^{CS}$  using (5.19)
  - 9: Set  $C_{rate} = \frac{P_{ij}^{CS}}{V_b A h r_j}$
  - 10: **if**  $C_{rate} \geq C_{cr}$  **then**
  - 11:      $C_{rate} = C_{cr}$
  - 12:     Compute  $P_{ij}^{CS}$  using (5.21)
  - 13: **end if**
  - 14: Set  $E^{CS} = \sum_{i=1}^n E_i^{CS}$
  - 15: Compute  $P_{AG}$  and  $P_i^{fact}$  using (5.11) and (5.13)
  - 16: Set  $P_i^{ref} = P_i^{fact} * P_{AG}$
  - 17: Compute  $V = V_{ref} + k(P_i + P_i^{ref})$
  - 18: Compute  $SOC_j(t)$  using (5.27)
- 

CSs are assumed to be equipped with charging points which can charge and discharge their batteries. Table 5.1 shows the specifications and parameter associated with batteries considered in the simulation. Table 5.2 shows the different simulation parameters used in the proposed work. It can be seen from the table that the minimum and the maximum SOC limit of the batteries are 20% and 100% respectively. A typical MG has been modelled to verify the proposed DBC.

The purpose of this work is to demonstrate the power distribution among the batteries present at different CSs. The distribution of power is based on power regulation signal which is obtained with the help of P/V droop method. MG senses the voltage of the node and based on the reference voltage, a power signal is generated. This signal is the regulated power which has to be shared by the three CSs. Each CS has different batteries with different energy capacities. The distribution of power among the batteries present at any CS is shared based on their present SOC and droop participation factor. The batteries having higher capacities will share the larger power and vice-versa.

The solar and wind resources data for a location situated near Patiala, India is taken from the NASA surface meteorology website. Based on this data, the output of wind turbines and solar PV panels are evaluated using Eq. (2.1) and Eq. (2.4). Figure 5.6 (a) demonstrates

Table 5.2: Simulation parameters

Parameter	Value
Wind turbine	400 kW
Solar PV panel	1000 kW
FC	300 kW
Diesel generator	250 kW
Load (Residential, Industrial, Commercial)	0- 500 kW in each case
CS capacity	360 kWh
Nominal voltage	400 V
Peak load	1371 kW
$C_{rate}$ and $D_{rate}$	2
$SOC_{min}$	20%
$SOC_{max}$	100%

the solar radiation ( $kWh/m^2$ ) and wind speed ( $m/s$ ) on a particular day. Figure 5.6 (b) demonstrates the different powers generated by wind turbines, solar PV panels and FC on same day. Figure 5.6 (c) shows the total power generation, load demand and battery power on the same day. FC is used in the proposed MG owing to its high generation efficiency, reliability and long durability at rated power. The FC power is kept constant because it is treated as the base power plant. Even, when the load is low and power can be supplied through wind and solar, still FC is kept constant so that the surplus power can be used for charging the batteries. Based on the voltage variation on the MG and implementing the P/V droop characteristics, a power regulation signal has been obtained as shown in Figure 5.7 (a). As depicted in the figure, negative power implies that power is required at the MG and this power should be drawn from the batteries. However, positive power implies that power is available at the MG and this power could be fed to CSs to charge the batteries. After receiving power signal, DBC distributes the total power among three CSs as shown in Figure 5.7 (b). It is worth mentioning that CS with highest energy capacity shares more power as compared to the ones with having low energy capacity.

The distribution of the power among different CS is handled by altering the  $C_{rate}$  and  $D_{rate}$  of their individual batteries. It has been observed from the Figure 5.8 that  $C_{rate}$  of the batteries are different for different CSs. This implies that the  $C_{rate}$  of the individual batteries are different due to their different capacities. Similar observation can also be seen for the  $D_{rate}$  in Figure 5.8. SOC analysis at different CSs has been shown in Figure 5.9. As an example, two sets of 16 kWh battery has been considered to demonstrate the proposed methodology. As

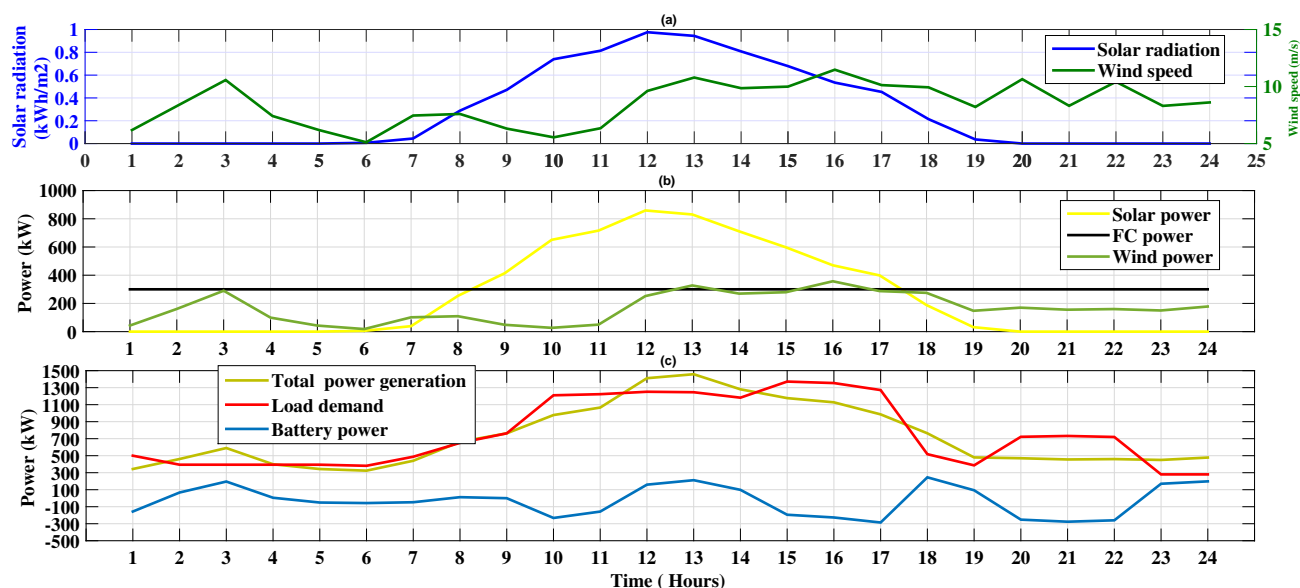


Figure 5.6: (a) Solar radiation ( $KWh/m^2$ ) and wind speed ( $m/s$ ) (b) Power generation by various RESs at MG (c) Total power generation, load demand and battery power requirement (charging and discharging mode).

seen in Figure 5.9 (a), initially battery 1 has 90.8 % of SOC while battery 2 has 92.4 % of SOC. These SOC values are randomly generated at each CS. It can be seen from Figure 5.7 that at 0100 hour, the power signal is negative, therefore the batteries need to be discharged. As seen from Figure 5.9 (a) that at 0100 hour, the SOC values of the batteries have been decreased. Similarly, at 0200 hour the power signal is positive (Figure 5.7), therefore, the batteries will be charged. As seen from Figure 5.9 (a) that at 0200 hour, the SOC values of the batteries have been increased. This has happened due to charging of the batteries. Similar observations can be inferred from the power signal as shown in Figure 5.7 (a) and SOC variations shown in Figure 5.9 (b) & Figure 5.9 (c) for CS2 and CS3. It can be inferred from the figure that energy changes with respect to time. Figure 5.9 (d) demonstrates the complete energy variation in all six kinds of batteries of CS1. It can be seen that SOC of the individual battery on a particular CS varies according to the power available or required at MG. Further, it can be seen from the Figure 5.9 (a) that at 2100 hour, batteries attain  $SOC_{min}$  and at 2200 hour, batteries are no longer able to provide any power to the MG. Further, it can be validated from Figure 5.8 that at 2200 hour, there is no charging or discharging in the batteries at any CS. Finally, Figure 5.10 depicts a comparison between the regulation signal received at AG and power met by batteries present at the CSs. It is also worth noting that at most of the times, batteries are capable to handle the power regulation signal. However, at certain hours when the power required is more and batteries and

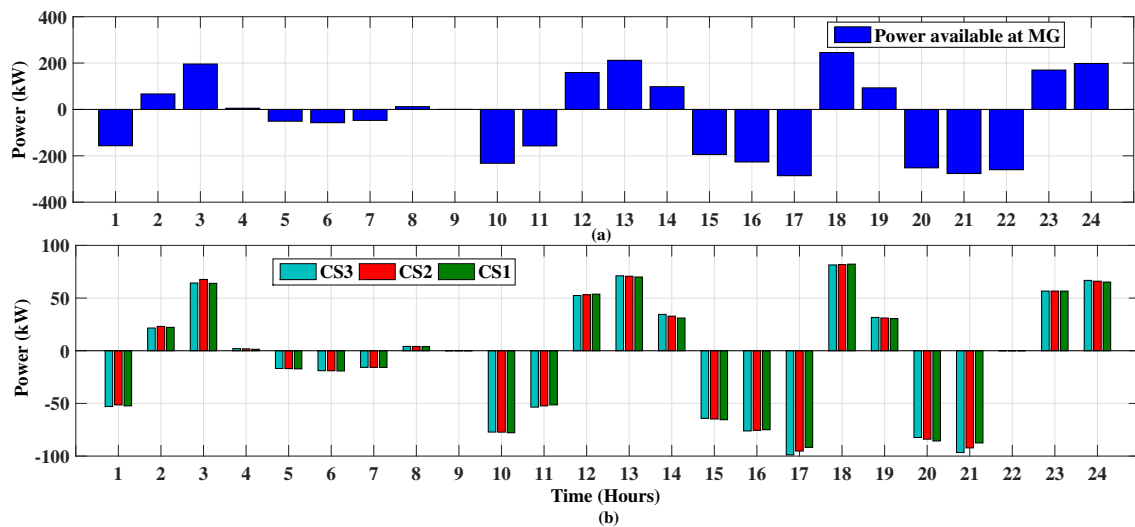


Figure 5.7: (a) Power available at MG (b) Power distribution at different CSs

RESs are not able to supply the require power, a DG is run to meet the power requirement. Figure 5.10 shows the power mismatch between the CSs and MG and power generated by the DG. The above simulation results clearly indicate that the power regulation signal can be easily handled with the batteries with different ratings placed at the CSs. In the following sub section, one critical case such as sudden failure of solar power source is discussed and also a brief comparison between the existing and proposed work is presented in subsequent subsection.

#### 5.4.1 Special case study: solar power breakdown

In this sub section, a special case study where the sudden shutdown of solar power plant has been considered. Figure 5.11 clearly highlights that the solar power plant at 0800 hours had stopped working. This shutdown of energy from solar power plant leads to demand supply variations. In this particular case, the demand of  $650 \text{ kW}$  exceeds the generation capacity of  $409 \text{ kW}$ . This situation generates a regulation signal of  $-241 \text{ kW}$  which is required from batteries available different CSs to discharge more energy.

In the considered simulation setup, 3 CSs with different battery sets have been considered which cater this regulation signal of  $-241 \text{ kW}$ . The related results have been presented in Figure 5.12. In this figure, the SOC variations of batteries at different CSs have been depicted. For instance, in order to compensate the said regulation signal, Type 1 batteries available at CS1, CS2 and CS3; discharge more energy and attain SOC's equivalent to 66.48%, 52.97% and 55.64% respectively. Similarly, Type II batteries reduce this SOC level to 66.48%, 54.30% and

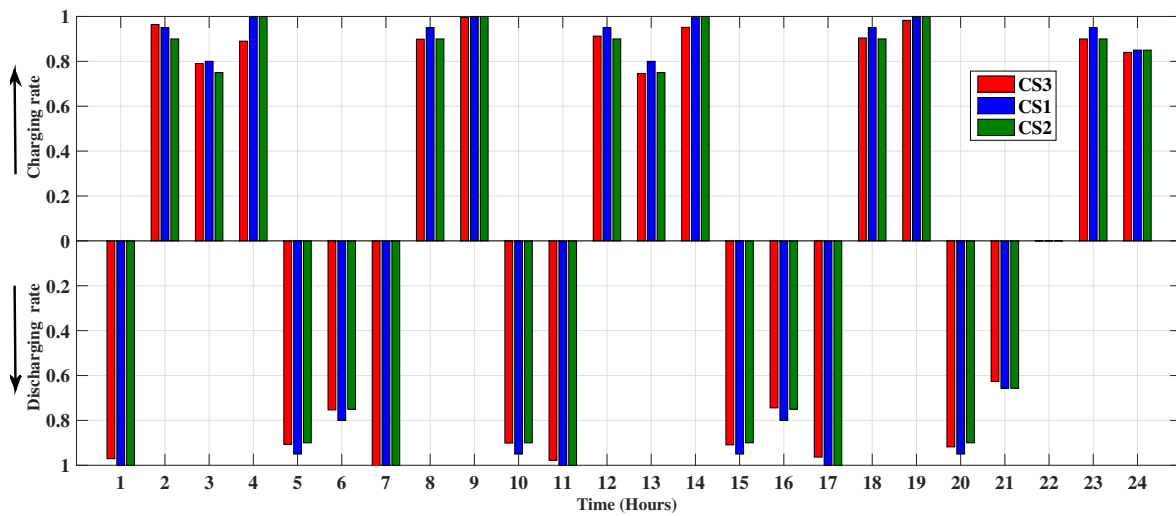


Figure 5.8: Charging and discharging rates at different CSs

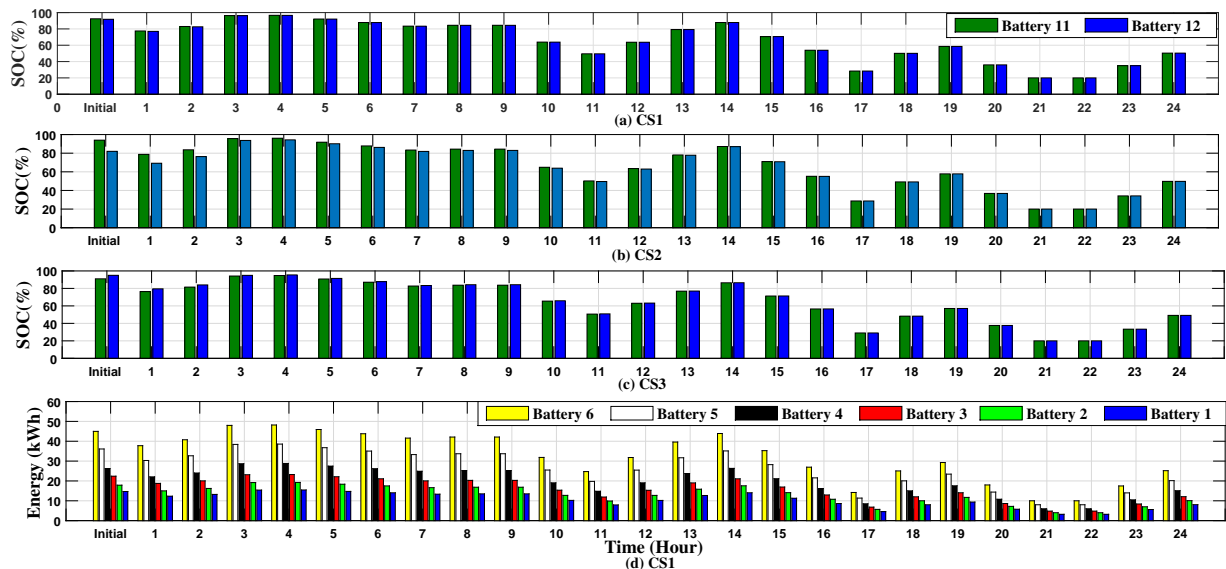


Figure 5.9: Battery SOC variations at different CSs

55.64% respectively. These SOC variations are pretty much on a higher end in comparison to a case wherein solar power plant functions properly as shown in the previously discussed segments (refer Figure 5.9). Additionally, the results also showcase that the proposed scheme manages the demand-supply variations even under sudden shutdown of any energy source.

## 5.4.2 Comparison with the existing scheme

This subsection highlights the detailed comparison of the proposed scheme with an existing scheme. For the purpose of this comparison, same set of parameters as highlighted in previ-

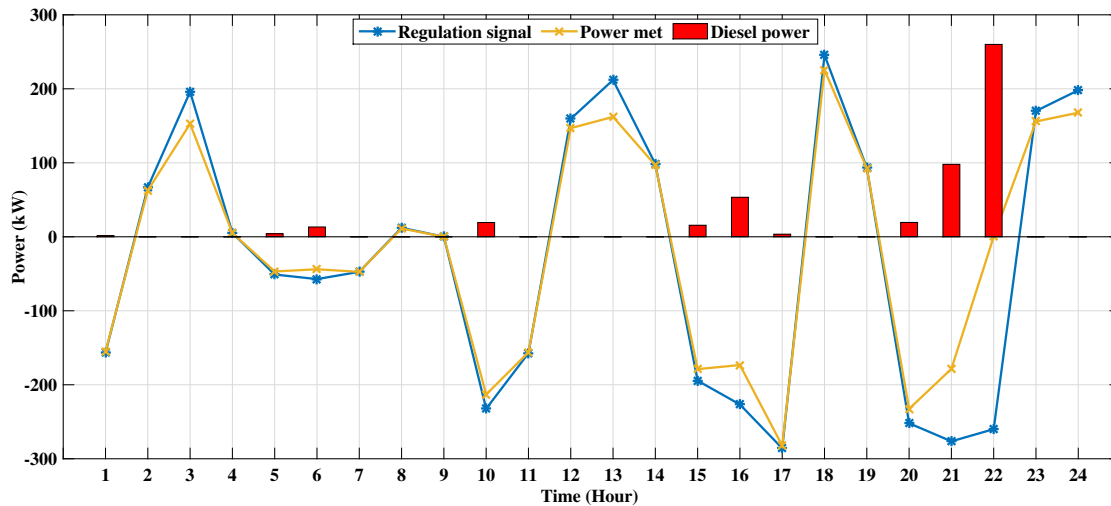


Figure 5.10: Total power met using regulation signal and diesel generator

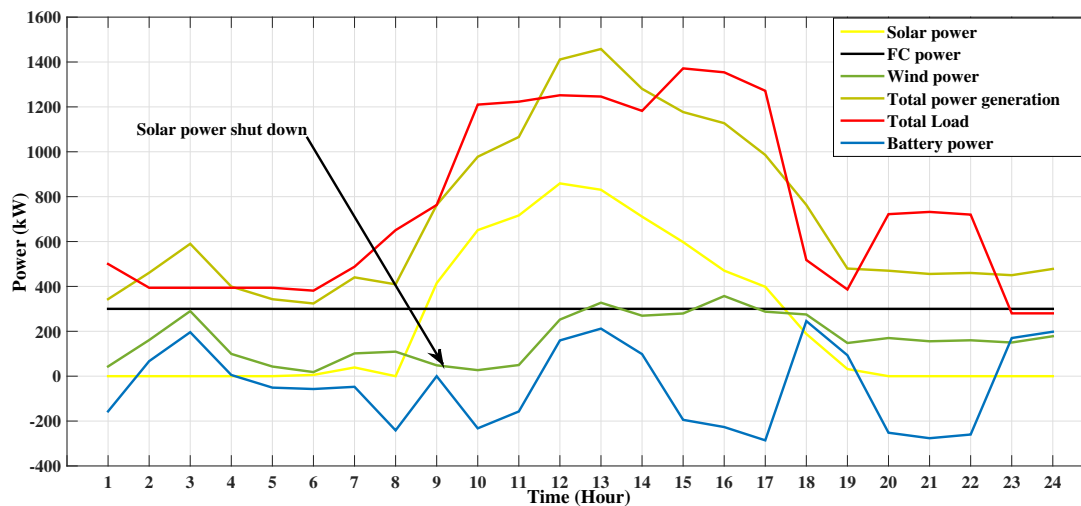


Figure 5.11: The solar power is shut down at 0800 hour

ous segments have been considered. The comparison results of both the schemes have been depicted using Figure 5.12. This figure illustrates the SOC variations of Type I batteries at CS1 across 24 hours time period. It is evident from the figure that the batteries involved in MG power stabilization using the proposed scheme yield better results than the batteries being utilized using the existing scheme. For instance, at 0700 hour regulation signal of  $-47.37 \text{ kW}$  was generated as shown in Figure 5.7 (a). In order to compensate these variations, the batteries (following the proposed scheme) at CS1 reduced their respective SOC levels to 81.48% which has comparatively greater than the SOC variations as per the other scheme. It is worth mentioning that batteries using both the schemes started with the same initial SOC levels of 92%.

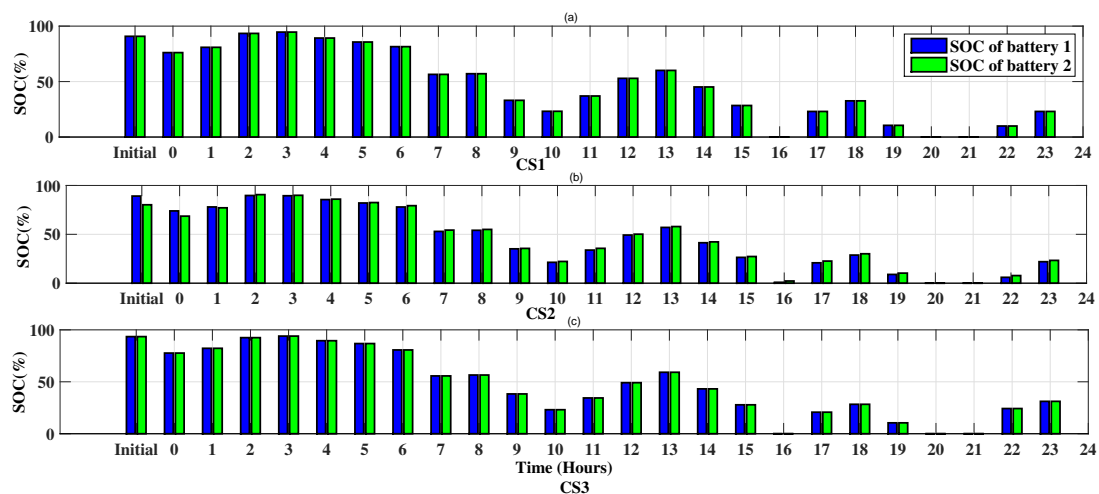


Figure 5.12: Battery SOC variations at different CSs during sudden shutdown of solar power plant

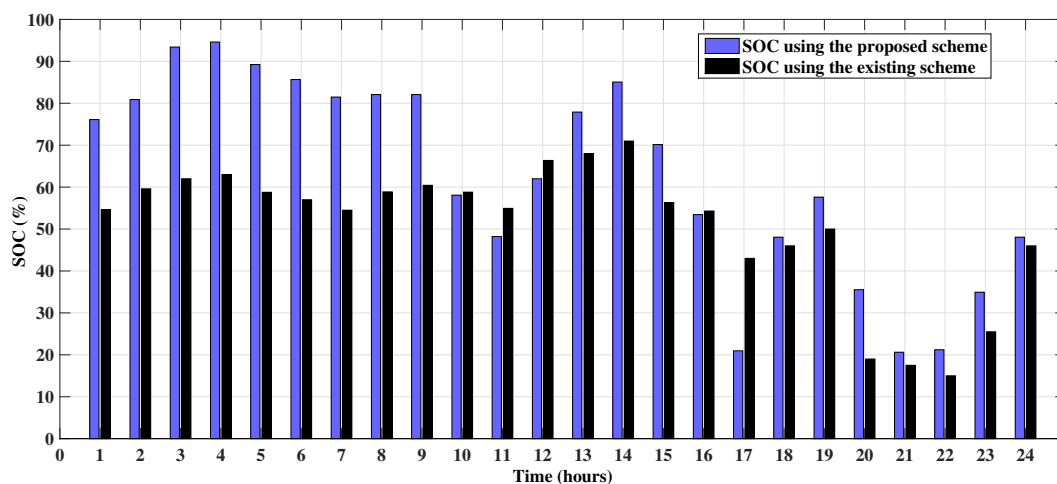


Figure 5.13: Comparison of the proposed scheme with an existing scheme with respect to battery SOC variations (battery 1).

The reason behind the above mentioned differences in the two schemes, can be attributed to their respective methodologies. The existing scheme considers the charging and discharging of batteries according to the regulation signal. However, it segregates and aligns the batteries in either charging or discharging operations; thereby limiting the regulation capacity of batteries. On the other hand, the proposed scheme is more flexible in its approach and involves all the batteries in managing the regulation signals. Additionally, the proposed scheme also alters the charging and discharging rates of the batteries to provide greater MG

support unlike the existing scheme. Due to these differences, the proposed scheme outperforms the existing scheme in majority of the cases.

### **5.5 Conclusion**

In this chapter, MG interactions with the DESS has been investigated. The batteries present at the CS can be small batteries, or batteries of PHEVs. The main purpose of this chapter has been to control the charging and discharging rates of the batteries present at the CSs to handle intermittency issues related to the RESs. Power management of the MG has been achieved using the droop control techniques. Based on the voltage deviation, the regulated power signal is obtained and this regulated signal is shared among individual batteries participating in the MG support. It has been observed that different batteries with the different charging and discharging rates can handle the intermittency of RESs. This scheme is very useful for the DESS which are going to be one of the new storage technology for MGs. The simulation results proved that the DESS can effectively handle power management in the suggested MG using droop based technique. Impact of variations of the SOC of batteries on a particular CSs have been discussed in case of sudden failure of one of renewable energy source. The results have been compared with the existing system and it is found that the proposed system performs satisfactory.

## Chapter 6

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### CONCLUSION AND FUTURE SCOPE

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#### 6.1 Conclusions from the present work

A hybrid energy system is proving to be a more economical and suitable source of electricity, particularly for off-grid or isolated locations. Moreover, two major factors associated with hybrid systems are the price of electricity and the reliability of the system. An optimal system design must be economical and reliable, and it can be achieved with the help of proper selection of components of the system. It has been observed from a detailed literature review that many conventional and non-conventional methods have been applied by various researchers for cost analysis and power management of hybrid energy systems. Apart from these techniques, various software tools have been designed for system sizing. It was observed in the past few years that the use of evolutionary algorithms has increased drastically for designing renewable-based hybrid energy systems. Each optimization technique and tool has its own features and potential to significantly promote the applicability of renewable energy generation. The chapter-wise conclusion of the research work has been presented below,

Chapter 1, provides a detailed overview of the optimization techniques for sizing, design, planning and control problems in the field of hybrid energy systems consisting of RESs. It can be concluded from the literature that there are many optimization methods and tools available that can be applied to make a hybrid energy system more economical and efficient. The detailed comparisons of the different approaches have been presented in brief.

In chapter 2, a hybrid system consists of solar PV panels, wind turbines with battery storage has been modeled to meet the load demand of a small area. The resource data such as solar radiation, wind speed and component costs have been collected for one year. A complete detailed mathematical operational strategy has been presented. In order to evaluate the LCOE, a meta-heuristic algorithm i.e. ABC has been applied. A brief introduction of the algorithm

is presented with detail operational steps. The results obtained from ABC algorithm have been compared with other technique such as PSO algorithm and software tool HOMER. Further, it is found that a ABC algorithm provides a competitive results. It can be concluded from the study that optimal hybrid system satisfactorily satisfy the load demand without violating any constraints. Further, different case studies have been analyzed and it is found that the LCOE is highest when load is met by diesel generator. It is also observed that hybrid PV-wind-battery system may be a suitable choice for off grid locations.

In chapter 3, an another renewable energy source i.e., biomass have been introduced in the system. This hybrid system consists of wind, PV and biomass with battery storage has been proposed to satisfy the energy needs of the small rural area. A simplified operational strategy have been developed for smooth operation of the system. The testing and validation of the model outputs is performed with the help of three optimization technique i.e., ABC, PSO and HOMER. A brief comparison of the results obtained by the various method is presented. Further, to check the robustness of the algorithms a robustness test is also performed. Performance and reliability of the proposed system in the critical cases such as failure of any generating unit has been observed. It is observed that inclusion of biomass power in hybrid energy system enhances the reliability of the hybrid wind-solar system. Moreover, the electricity demand could be met by utilizing the natural resources which is not properly utilized in developing countries.

Chapter 4, presents an optimal sizing methodology and cost analysis for a stand-alone and grid connected PV-biomass hybrid energy system. The power is purchased from grid when required and sold to grid when there is excess of power. A detailed mathematical operational strategy have been presented. Further, ABC algorithm is used to detect the optimum hybrid system configuration with the least LCOE while minimizing ASC. It has been observed that a grid connected hybrid PV-biomass system is cost effective and reliable choice for rural electrification as compared to stand-alone hybrid PV-biomass energy system. A brief comparison of results obtained from the ABC algorithm and HOMER has been carried out. Moreover, it is also observed from the results that the ABC algorithm provides better results as compared to HOMER. The results obtained clearly show that grid connected hybrid system may be a cost effective electrification solution for numerous villages in developing countries.

Chapter 5 mainly emphasizes on optimal power management of a hybrid energy system consisting of RESs and distributed energy storage system. The power is managed with

the help of controlling the charging and discharging rates of individual battery. A droop based controller is proposed for optimal power management of batteries. An aggregator has been suggested at the MG which distributes the power among the various CS and each CS finally distributes the power among the individual batteries based on droop participation factor. Moreover, the charging and discharging rates of batteries are controlled to achieve the desired power flow between the microgrid and CSs. Impact of variations of the SOCs of batteries on a particular CSs have been discussed in case of sudden failure of one of renewable energy source. The results have been compared with the existing system and it is found that the proposed system performs satisfactory.

### **6.2 Futuristic aspects**

- The evolutionary algorithm proposed in this work may be further applied to more complex hybrid systems for cost analysis and power management.
- Detailed mathematical modeling proposed might be useful for designing new and improved hybrid systems.
- The control strategy can be developed to manage proper power flow in hybrid energy system

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