Optimized Operation of Distributed Renewable Energy Sources in Smart Grid

Thesis submitted to the
Cochin University of Science and Technology
for the award of the degree of
Doctor of Philosophy
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By
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Under the guidance of
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June 2015

Dedicated to my Husband Kavidas
and Daughters
Devika Das, Darshana Das

Division of Electrical Engineering
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2015

Certificate

This is to certify that the work presented in this thesis entitled "**Optimized Operation of Distributed Renewable Energy Sources in Smart Grid**" is based on the authentic record of research done by **C. P. Vineetha** under my guidance towards the partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** of the Cochin University of Science and Technology and has not been included in any other thesis submitted for the award of any degree.

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Declaration

I hereby declare that the work presented in this thesis entitled "**Optimized Operation of Distributed Renewable Energy Sources in Smart Grid**" is based on the original research work carried out by me under the supervision and guidance of **Dr. C. A. Babu**, Professor, Division of Electrical Engineering, School of Engineering, Cochin University of Science and Technology, Kochi-22 and has not been included in any other thesis submitted previously for the award of any degree.

Kochi **C. P. Vineetha**
22nd June 2015

Curriculum Vitae

C. P. Vineetha was born in Thrissur District of Kerala, India in 1972. She obtained B.Tech Degree in Electrical and Electronics Engineering from Govt. Engineering College, Thrissur, Kerala under Calicut University, Kerala in 1993. She acquired M.Tech in Power System from the same college with project work on Fuzzy Load Frequency Control of Power System in the year 2005. She has 4 years of managerial and technical experience in the electronic industry Volta Electronics, Thrissur, Kerala. She got selected in Kerala State Electricity Board Limited, an electrical utility company in Kerala as Assistant Engineer in 1998 and now in the post of Assistant Executive Engineer. She has wide experience in electrical transmission and distribution sectors. She is a corporate member of the Institution of Engineers (India) and Chartered Engineer (India). She has graduate student membership in IEEE, IAS, IEEE Smart Grid Community and IEEE Young Professionals. She attended IEEE conferences for paper presentation in India and abroad. She has so far published one research paper in international journal and two others are under review. Her areas of interest include power system, renewable energy, distributed generation, energy management and smart grid.

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C. P. Vineetha

Abstract

The renewable energy sources (RES) will play a vital role in the future power needs in view of the increasing demand of electrical energy and depletion of fossil fuel with its environmental impact. The main constraints of renewable energy (RE) generation are high capital investment, fluctuation in generation and requirement of vast land area. Distributed RE generation on roof top of buildings will overcome these issues to some extent.

Any system will be feasible only if it is economically viable and reliable. Economic viability depends on the availability of RE and requirement of energy in specific locations. This work is directed to examine the economic viability of the system at desired location and demand.

The RES of hybrid power system (HPS) proposed in this work are solar photovoltaic (PV) and wind mill. Inverter with maximum power point tracking (MPPT) controllers is also part of the system to convert DC to AC and extract maximum power from these sources. Systems are considered with or without energy storage device. The energy flow can be unidirectional or bidirectional. Technical and commercial models are developed for each component of HPS. Three configurations are considered in accordance to the energy flow and availability of storage device. They are conventional grid tied system, smart grid tied system and smart grid tied system with storage. System models and algorithms are developed for each of these configurations for HPS and individual RES to determine optimal system satisfying the constraints appropriate for each configuration. Green energy credit (GEC), possible CO_2 emission reduction, peak energy credit (PEC) due to peak demand reduction and state of charge (SOC) of storage battery are considered in the development of algorithm. To test the algorithm three sample locations are selected based on availability of RE and two types of load curve, one lightly loaded and the other heavily loaded.

Sensitivity analysis is conducted to find out the variation in optimal cost by the change in the utility energy cost and component cost of HPS. Finally optimal systems for all three configurations are compared to determine most feasible system for the desired location and load. The results are presented.

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List of Abbreviations

AGM	-	Absorbed Glass Mat
AMI	-	Advanced Metering Infrastructure
AMR	-	Automatic Meter Reading
AT&C	-	Aggregate Technical and Commercial
B	-	Battery
BELED	-	Break Even Line Extension Distance
CFL	-	Compact Fluorescent Lamp
Con	-	Conventional
CRF	-	Capital Recovery Factor
DA	-	Distribution Automation
DG	-	Distributed Generation
DOD	-	Depth of Discharge
DR	-	Demand Response
FACTs	-	Flexible AC Transmission System
FC	-	Fuel Cell
GEC	-	Green Energy Credit
GHG	-	Green House Gas
HAWT	-	Horizontal Axis Wind Turbines
HPS	-	Hybrid Power System
IC	-	Inverter with MPPT Controller
ICC	-	Initial Capital Cost
IEA	-	International Energy Agency
IPP	-	Independent Power Producers
LED	-	Light Emitting Diode
loc	-	Location

MPPT	-	Maximum Power Point Tracker
O&M	-	Operation and Maintenance
PEC	-	Peak Energy Credit
PM	-	Particulate Matter
PV	-	Photovoltaic
REO	-	Renewable Energy Obligation
RES	-	Renewable Energy Sources
SA	-	Substation Automation
SOC	-	State of Charge
STC	-	Standard Test Condition
T&D	-	Transmission and Distribution
TOD	-	Time of Day
VAWT	-	Vertical Axis Wind Turbines
VRLA	-	Valve Regulated Lead Acid
W	-	Wind Mill

List of Nomenclature

Symbols

α	Rate of interest in %
β	Life span of component in years
ω	Life span of project in years
λ	Desired value of average SOC in %
ε	Subsidy on the initial capital investment of HPS in %
τ	Turn of replacement
$\hbar$	Per unit peak energy credit in INR
$\wp$	Allowable dump load in %
ψ	Connected load of the premises in kW
ξ	Monthly fixed charge of the premises per kW in INR
Λ	Factor of average consumption of premises at normal and peak hours to limit Maximum RE to grid in %
□	Minimum peak demand reduction in %
η_s	Efficiency reduction per year of PV module due to ageing in %
η_v	Efficiency reduction due to losses in inverter and MPPT controller in %
η_w	Efficiency reduction per year of wind mill due to ageing in %
η_b	Charging efficiency of storage battery in %
χ_b	Net investment cost of 1kW battery in INR
χ_s	Net investment cost of 1kW PV module in INR
χ_v	Constant of variable component of net investment of inverter with MPPT controllers
χ_w	Constant of variable component of net investment of wind mill
σ_v	Constant of fixed component of net investment of inverter with MPPT controllers
σ_w	Constant of fixed component of net investment of wind mill

δ_b	Initial investment cost of 1kW battery in INR
δ_s	Initial investment cost of 1kW PV module in INR
δ_v	Constant of variable component of initial investment of inverter with MPPT controllers
δ_w	Constant of variable component of initial investment of wind mill
λ_v	Constant of fixed component of initial investment of inverter with MPPT controllers
λ_w	Constant of fixed component of initial investment of wind mill
γ_t	Global horizontal irradiance at time t in kW/m^2
ω_τ	Life span of wind mill in years at τ^{th} replacement
Δ_{ij}	CO$_2$ emission reduction for PV module rating i and wind mill rating j in kg
$\phi c_{dt_{ij}}$	Energy to charge battery at time t and day d for PV module rating i and wind mill rating j
$\phi dc_{dt_{ij}}$	Energy discharge from battery at time t and day d for PV module rating i and wind mill rating j
$\phi dc_{dt_{ijk}}$	Energy discharge from battery at time t and day d for PV module rating i, wind mill rating j and battery rating k
A_{11}	Initial capital investment in INR
A_{22}	Present O&M cost in INR
A_{33}	Present insurance charge in INR
A_{44}	Present salvage in INR
A_{1b_k}	Capital investment of battery with CRF of rating k in INR
A_{2b_k}	Life time O&M cost of battery with g and h of rating k in INR
A_{3b_k}	Life time Insurance charge of battery with g and h of rating k in INR
A_{4b_k}	Salvage value of battery with h and q of rating k in INR
A_{5b_k}	Replacement cost of battery with h and q of rating k in INR

A_{1s_i}	Initial capital investment of PV module with CRF of rating of i in INR
A_{2s_i}	Life time O&M cost of PV module with g and h of rating of i in INR
A_{3s_i}	Life time insurance charge of PV module with g and h of rating of i in INR
A_{4s_i}	Salvage value of PV module at the end of project with h and q of rating of i in INR
A_{1v_x}	Capital investment of inverter with MPPT controller with CRF of rating x in INR
A_{2v_x}	Life time O&M cost of inverter with MPPT controller with g and h of rating x in INR
A_{3v_x}	Life time Insurance charge of inverter with MPPT controller with g and h of rating x in INR
A_{4v_x}	Salvage value of inverter with MPPT controller with h and q of rating x in INR
A_{5v_x}	Replacement cost of inverter with MPPT controller with h and q of rating x in INR
A_{1w_j}	Capital investment of wind mill with CRF of rating of j in INR
A_{2w_j}	Life time O&M cost of wind mill with g and h of rating of j in INR
A_{3w_j}	Life time insurance charge of wind mill with g and h of rating of j in INR
A_{4w_j}	Salvage value of wind mill at the end of the project with h and q of rating of j in INR
A_{5w_j}	Replacement cost of wind mill with h and q of rating of j in INR
A_{11b_k}	Initial capital investment for battery of k rating
A_{11s_i}	Initial capital investment for PV modules of i rating
A_{11v_x}	Initial capital investment of inverter with MPPT controller of rating x in INR

A_{11w_j}	Initial capital investment of wind mill of rating of *j* in INR
c	Number of replacement in the project life time
C_{ζ}	Off grid premises fixed charge for the life span of project in INR
C_{Θ}	Net cost of conventional energy in INR
C_{b_k}	Net investment of battery bank for the life span of project of rating *k* in INR
C_{s_i}	Net investment cost of PV module for the life span of project of rating *i* in INR
$C_{v\square_x}$	Net investment cost of conventional grid tied inverter with MPPT controllers for the life span of project of rating *x* in INR
$C_{v\approx_x}$	Net investment cost of smart grid tied inverter with MPPT controllers for the life span of project of rating *x* in INR
$C_{v\cong_x}$	Net investment cost of smart grid tied inverter with storage and MPPT controllers for the life span of project of rating *x* in INR
C_{w_j}	Net investment cost of wind mill for the life span of project of rating *j* in INR
$C_{\pi_{ij}}$	Conventional grid premises utility energy cost for the life span of the project for PV module rating *i*, wind mill rating *j* in INR
$C_{\varphi_{ij}}$	Net energy cost of conventional grid premises for the life span of the project for PV module rating *i*, wind mill rating *j* in INR
$C_{\gamma_{ij}}$	Smart grid tied premises utility energy cost for the life span of the project for PV module rating *i*, wind mill rating *j* in INR
$C_{\partial_{ij}}$	Smart grid tied premises RE cost delivered to grid for the life span of the project for PV module rating *i* wind mill rating j in INR
$C_{\varpi_{ij}}$	Cost of smart meter for PV module rating *i*, wind mill rating *j* in INR
$C_{\Phi_{ij}}$	Net energy cost of smart grid tied premises for the life span of the project for PV module rating *i*, wind mill rating *j* in INR

$C_{\vartheta_{ij}}$	Smart grid tied premises with storage RE cost delivered to grid for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\theta_{ij}}$	Net energy cost of smart grid tied premises with storage for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\mu\square_{ij}}$	Green energy credit for PV module rating i, wind mill rating j in INR
$C_{\mu\approx_{ij}}$	Green energy credit of smart grid tied system for PV module rating i, wind mill rating j in INR
$C_{\mu\cong_{ij}}$	Green energy credit of smart grid tied system with storage for PV module rating i, wind mill rating j in INR
$C_{\rho_{ij}}$	Peak energy credit for PV module rating i, wind mill rating j in INR
$C_{\pi m_{ij}}$	Conventional grid premises utility energy cost at peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\pi n_{ij}}$	Conventional grid premises utility energy cost at normal hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\pi o_{ij}}$	Conventional grid premises utility energy cost at off peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\gamma m_{ij}}$	Smart grid tied premises utility energy cost at peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\gamma n_{ij}}$	Smart grid tied premises utility energy cost at normal hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\gamma o_{ij}}$	Smart grid tied premises utility energy cost at off peak hours for the life span of the project for PV module rating i, wind mill rating j in INR

$C_{\partial m_{ij}}$	Smart grid tied premises RE cost delivered to grid at peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\partial n_{ij}}$	Smart grid tied premises RE cost delivered to grid at normal hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\partial o_{ij}}$	Smart grid tied premises RE cost delivered to grid at off peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\vartheta m_{ij}}$	Smart grid tied premises with storage RE cost delivered to grid at peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\vartheta n_{ij}}$	Smart grid tied premises with storage RE cost delivered to grid at normal hours for the life span of the project for PV module rating i, wind mill rating j in INR
$C_{\vartheta o_{ij}}$	Smart grid tied premises with storage RE cost delivered to grid at off peak hours for the life span of the project for PV module rating i, wind mill rating j in INR
d	Day of the year
$E_{g_{ij}}$	Renewable energy generated for PV module rating i and wind mill rating j in kWh
E_{ij}	Excess of energy generated in a premises for PV module rating i and wind mill rating j in kWh
$E_{n\partial_{ij}}$	Smart grid tied premises RE delivered to grid at normal hours for PV module rating i, wind mill rating j in kWh
$E_{o\partial_{ij}}$	Smart grid tied premises RE delivered to grid at off peak hours for PV module rating i, wind mill rating j in kWh
$E_{n\vartheta_{ij}}$	Smart grid tied premises with storage RE delivered to grid at normal hours for PV module rating i, wind mill rating j in kWh
$E_{o\vartheta_{ij}}$	Smart grid tied premises with storage RE delivered to grid at off peak hours for PV module rating i, wind mill rating j in kWh

$E_{\varsigma m_{ij}}$	Reduction of peak consumption from grid for PV module rating *i* and wind mill rating *j* in kWh
E_{lm}	Peak demand of the premises in kWh
$E_{\varsigma m\%_{ij}}$	Percentage reduction of peak demand for PV module rating i, wind mill rating *j*
$E_{\varsigma m_{ijk}}$	Reduction of peak consumption from grid for PV rating *i*, wind mill rating *j* and battery rating k in kWh
$E_{dump_{ij}}$	Dump load of the premises for PV module rating *i* and wind mill rating *j* in kWh
El	Demand of the premises in kWh
f	Surface porosity coefficient
g	Escalation rate in %
h	Interest rate evolution in %
H_{∇}	Desired height of wind mill in m
H_z	Measured height of wind speed in m
i	Rating of PV module in kW
i_{Ω}	Increment of PV module rating for simulation
$i_{\max}$	Maximum rating of PV modules in kW
$i_{\min}$	Minimum rating of PV modules in kW
INR	Indian Rupees
j	Rating of wind mill in kW
j_{Ω}	Increment of wind mill rating for simulation
$j_{\max}$	Maximum rating of wind mill in kW
$j_{\min}$	Minimum rating of wind mill in kW
k	Rating of battery in kW
k_{ij}	Rating of battery for PV module rating *i* and wind mill rating *j* in kW
$k_{ij\max}$	Maximum rating of battery for PV module rating *i* and wind mill rating *j* in kW

$k_{ij\min}$	Minimum rating of battery for PV module rating i and wind mill rating j in kW
$Ps_{\kappa i}$	Rated power output of PV module of i rating in kW
$Pw_{\kappa j}$	Rated output power of a wind mill of j rating in kW
Pl_{dt}	Demand of the premises at time t and on day d in kW
Ps_{t_i}	Output power of PV module of rating i at time t in kW
Pw_{t_j}	Output power of wind mill of rating j at time t in kW
Ps_{dt_i}	PV module output power of rating i at time t and on day d in kW
Pw_{dt_j}	Wind mill output power of rating j at time t and on day d in kW
q	General inflation rate in %
r_m	Per unit grid peak energy cost in INR
r_n	Per unit grid normal energy cost in INR
r_o	Per unit grid off peak energy cost in INR
$r_{\partial m}$	Per unit cost of peak energy delivered to grid in INR
$r_{\partial n}$	Per unit cost of normal energy delivered to grid in INR
$r_{\partial o}$	Per unit cost of off peak energy delivered to grid in INR
Sw_{κ}	Rated wind speed in m/s
Sw_t	Wind speed at time t at desired height in m/s
Sw_{ci}	Cut in wind speed in m/s
Sw_{co}	Cut out wind speed in m/s
Sw_{zt}	Wind speed at time t at measured height in m/s
$SOC_{a_{ij}}$	Average SOC of the battery for PV module rating i, wind mill rating j in %
$SOC_{\max}$	Maximum SOC of the storage battery in %
$SOC_{\min 1}$	Minimum SOC of the storage battery at peak hours in %
$SOC_{\min 2}$	Minimum SOC of the storage battery at other times of the day in %

$SOC_{dt_{ij}}$	SOC of the battery at time t and on day d for PV module rating i and wind mill rating j
t	Time in hours
T_t	Temperature at time t in °C
T_{cp}	Temperature coefficient of PV module in %/°C
u	Minimum renewable energy generated in % of consumption of premises
x	Rating of Inverter with MPPT controllers in kW
y	Turn of the project year
-ve	Negative

List of Publications

International Journals:

1. C. P. Vineetha, C. A. Babu and T. N. P. Nambiar, “Optimization of grid tied hybrid power system in smart premises,” *International Journal of Green Energy , Taylor & Francis,* Available Online 15th Sep. 2014.
2. C. P. Vineetha and C. A. Babu, “Optimization of hybrid power system connected to single directional grid,” *International Journal of Energy Technology & Policy, Inder Science,* Accepted for Publication.
3. C. P. Vineetha and C. A. Babu, “Optimal unidirectional grid tied hybrid power system for peak demand management,” *Advances in Energy Research*, *An International Journal*, Accepted for Publication.

International Conferences:

1. C. P. Vineetha and C. A. Babu, “Smart grid challenges, issues and solutions,” *The 2014 International Conference on Intelligent Green Building and Smart Grid IEEE*, Paper ID: 230033 24-25 Apl. 2014, at Taipei, Taiwan.
2. C. P. Vineetha and C. A. Babu, "Economic analysis of off grid and on grid hybrid power system," *International Conference on Circuits, Power and Computing Technologies 2014 IEEE* , pp. 473-478, 20-21 Mar. 2014, Kumaracoil, Thukalay, Tamilnadu, India.
3. C. P. Vineetha and C. A. Babu, “Cost effectiveness of renewable energy sources in smart premises,” *Global Humanitarian Technology Conference: South Asian Satellite 2013 IEEE* pp. 159-163, 23-24 Aug. 2013, Thiruvanathapuram, Kerala.

Chapter 1

Introduction

1.1 Background

The operation of conventional thermal power plant caused green house gas (GHG) emission which results in global warming and climate change [1]. Kyoto Protocol on GHG reduction aims on reduction of new thermal power plant and promotion of renewable energy (RE) generation [2]. Also the cost fossil fuel is increasing and availability is decreasing drastically [1]. Fukushima nuclear disaster in Japan on 11th March 2011 forced many of the countries to rethink dependency on nuclear power [3]. The natural disaster at Kedarnath in India in June 2013 shows that the crowding of large hydro power plants in a small area affects the holding strength. Non RE sources are limited and uncontrolled utilization of these sources for energy generation may results in the annihilation of these sources [1].

It is expected that global energy demand will increase by one third from 2011 to 2035 as per International Energy Agency (IEA) [4]. The annual growth rate of demand of electric power is around 6.9% in a developing country like India [5] and it seems to continue in future due to increase in mechanization and overall industrial growth. Utilities are not able to meet the increase in requirement of customers, leading to load shedding or total black out. IEA projects that renewable energy sources (RES) like solar, wind, biomass, geo thermal, tidal, wave and small hydro will meet nearly half of this net increase in the energy demand [4]. RES are clean, safe, and easy to maintain [6], [7]. It is a sustainable method of generating power [1].

To minimize the gap in generation and demand, addition of grid tied RE generation system is being implemented world-wide which reduces the dependency on fossil fuels. It also reduces CO_2 emission and environmental degradation [1]. The limitations are fluctuation in power, requirement of large geographical area as well as higher cost of installation [7].

As an alternative distributed RE systems are proposed integrating with smart grid. Distributed RE generation near load centre results in low transmission and distribution (T&D) losses [7], [8]. In such systems RES are installed on roof top of the building and connected to the grid with provision for accepting energy from grid and delivering energy to the grid. The common RES are solar photovoltaic (PV) and wind mill due to their environmental friendly operation, abundant availability and easier installation [9]-[13]. For a given demand of the premises and utility tariff, economic viability of RE generation in the premises is dependent on the capacity of the grid to accept power from RES as well as the storage capacity of the premises. The cost constraint of utilization of distributed RES is to be determined for practical implementation of the system. The motivation of work comes from this concept. This work aims whether it is possible to find a financially feasible hybrid power system (HPS) on roof top of the premises connected to grid by drawing energy from utilities whenever required and injecting energy from HPS if possible over long period of time satisfying the constraints appropriate for the proposed systems. General models and algorithms are to be developed for different configurations of distributed RE generation to determine optimal systems.

The objective of work and organisation of thesis are shown here under.

1.2 Objective of Work

Distributed RE generation by providing HPS on the roof top of the premises are to be optimised according to the availability of the resources and demand for economical implementation of the system. This work aims to determine optimal HPS at any desired location and load for three different configurations of HPS connected to grid.

1. HPS with storage battery connected to single directional conventional grid (Conventional Grid Tied Hybrid Power System)
2. HPS connected to bidirectional smart grid (Smart Grid Tied Hybrid Power System)
3. HPS with storage battery connected to smart grid (Smart Grid Tied Hybrid Power System with Storage)

Based on the environmental conditions in South India three locations are selected for the study. In each location two typical hourly load curves for a year are taken.

The specific objectives are as follows:

- To develop model of the components of HPS for distributed RE generation. PV module and wind mill are taken as RES in this work. The solar lead acid battery is taken as storage device in those configurations where storage device is applicable. The inverter with MPPT controllers is the interlinking device of RES, storage battery and grid. Both technical and commercial modelling of each component of HPS has been carried out.

- To develop model and algorithm for conventional grid tied HPS to determine optimal system satisfying the objective function with appropriate constraints for this configuration. Optimal individual RES systems i.e., PV only and wind mill only system are also determined for this configuration.
- To develop model and algorithm for smart grid tied HPS to determine optimal system satisfying constraints appropriate for this configuration. Determination of optimal systems for individual RES is carried out for this configuration also.
- To develop model and algorithm for smart grid tied HPS with storage device satisfying objective function with constraints suitable for this configuration. Optimal systems for individual RES are also found out for this configuration.
- To analyse the optimal systems of all three configurations of HPS and individual RES in terms of RE generation, CO_2 emission reduction, RE to grid, SOC of the storage battery, peak demand reduction, optimal energy cost etc. The affect of peak energy credit (PEC) on the economics of the system implementation is also analysed.

1.3 Organisation of Thesis

Chapter 1 gives an overview of the work and organisation of the thesis.

Chapter 2 describes the RE integration with grid. A description of the proposed HPS is also given in this section. The functions and benefits of smart grid, smart meter and challenges of smart grid implementation are also mentioned in chapter 2. It discusses published works in the proposed areas.

The previous works are split into four groups as stand-alone HPS, conventional grid tied HPS, smart grid tied HPS and smart grid tied HPS with storage. The published optimization works for economic feasibility and technical feasibility, energy management and peak load management are discussed for various configurations.

Chapter 3 presents the technical and commercial modelling of HPS components. The initial capital investment of each component of the proposed HPS available from the literature and market are described in chapter 3. It also discusses cost of energy from utilities and methodology of work.

Chapter 4 describes conventional grid tied HPS in detail. The configuration and power flow of the proposed system are explained. The mathematical formulation of the system is carried out and algorithm is developed to determine optimal configuration for individual and combined RES satisfying constraints for the mentioned system. GEC is considered in mathematical formulation of the system. The model is applied in three locations for two different demand profiles to analyse the proposed algorithm.

Chapter 5 describes smart grid tied HPS. The mathematical formulation of the proposed system including constraints applicable for the better performance of the system is explained in detail. The algorithm to determine optimal configuration satisfying constraints is developed. Simulations are carried out for the same locations and loads applied for the conventional grid tied HPS.

Chapter 6 explains smart grid tied HPS with storage. The configuration of the proposed system with power flow is detailed in this section. The mathematical formulation of the system is discussed in detail with constraints applicable to the system. The algorithm to determine the optimal configuration is explained.

The model is applied at the same locations and loads applied for the previous systems to analyse the economic feasibility of the system.

Chapter 7 compares the proposed three configurations. Economic feasibility, peak demand reduction, impact of PEC and environmental impact are analysed to determine most feasible system for each location and load.

Chapter 8 summarises the works. The work is concluded in this section. The future scope of the work is also discussed at the end of the chapter.

Chapter 2

Literature Review

2.1 Introduction

Electricity was introduced in India by the British in 1879 by lighting bulbs on the streets of Calcutta. The Electricity Act of India was framed in 1910 [14]. At the time of independence in 1947 India was having generation of about 1360 MW, that too in a highly decentralized manner in and around urban areas [15]. It followed decades of development in power sector. Net result visible in this context has been formulation of state power grids, then regional grids, and now stepping towards evolution of national grid with transmission voltage increasing gradually from 132 kV to 765 kV class with intermediate voltages as 220 kV and 400 kV in AC system, while +800 kV in DC system [15]-[17] . Power Grid Corporation of India Limited will launch in nearby future 1200kV ultra high voltage test station with 1200kV experimental line in Bina, Madhya Pradesh [17]. Per capita energy consumption for the year 2012- 2013 stood at 917.18 kWh about 56 times greater than the per capita consumption in 1947 0f 16.3kWh [18]. Per capita consumption of world average in 2011 is 3045kWh which is very high compared to India's per capita consumption [19], [20]. Almost all the states in India are facing energy shortage with national average energy shortage of about 3.6 % for the financial year 2014-15 [21]. There is an increase of 215% for RES compared to 34.6% for thermal generation in 11th plan. This will continue in 12th plan also in view of the new policies of government to promote RES to meet the increasing demand [5], [22]. The estimated potential of grid interactive wind power is 49130MW and solar power is 20MW to 30MW per sqkm in India [23]. The achievement of RE generation in India is only 35766.96MW as on 31st March 2015 [24]. The total demand for electricity in India is expected to cross 950 GW by 2030 which is about 3.5 times demand in 2014 [21], [25]. RES will play a significant role to supply this increasing demand [14], [26]. The RES together with or without storage devices will form a HPS. This system can be grid connected with power flow from the grid to the HPS or in both direction with appropriate communication technology and smart metering. This may develop into a smart grid. Investigation of the economic aspect of HPS under different conditions of operation is the thrust of this work. This chapter reviews the published works related to these areas.

2.2 Renewable Energy Integration

There are several RES like solar, wind, geothermal, ocean, small hydro and biomass. If properly tapped, half of the energy demand can be met from RES [7], [21]. However some of the energy sources are intermittent in nature and energy has to be tapped whenever energy is available [12]. Installation of maximum power point tracking (MPPT) controller is required along with solar PV system and wind mill system to extract maximum power from these sources [44], [47]. So integrating these energy sources with grid have economical, technical and policy challenges.

High installation cost is the main reason for the low growth in tapping of RE. Sceptical attitudes towards RES on the part of energy planners, weak or non-existent policies to promote RES and lack of qualified personnel to design, manufacture, market, operate and maintain the RES are the causes for the dragging of wide implementation of RES [27], [115]. The non-availability of field performance data, inadequate documentation and evaluation of past experience, lack of clear priorities for future work and little or no information exchange on successful and unsuccessful projects are some of the obstacles for the fast development of RE as a source of electricity [7]. Wrong selection of site for implementation of RES and lack of technical personals are problems of RE integration [27], [28].

The fluctuating and unpredictable nature of RES like solar PV and wind mill requires complex technologies to integrate with existing grid [1], [9]. The harmonics developed from the complex power electronics circuits used for integration also causes many problems in the power system. The reliability of protection circuits to isolate RES from the existing grid whenever required is a great challenge in the integration of RES [27].

The power electronics circuits in inverter with MPPT controllers may cause harmonics in the power system. The flexible AC transmission system (FACTs) devices like static synchronous compensator, static series synchronous compensator and unified power flow controller will help to improve the stability and reliability of the grid which has large amount of RE penetration [27], [63]. The filter circuits provided with these systems will mitigate the harmonics injected into the grid due to power electronics circuits. Real-time computer controllers which can implement advanced and complex algorithms also help to extract maximum power from RES and reduce fluctuation in the RE generation. It also protects the storage battery from over charging. This will enhance the life of storage device.

It is more economical and grid friendly if the fluctuated power generated by the RES is utilised for irrigation purposes. The fluctuation in RE generation can also be reduced by distributed RE generation from a larger geographical area with small power plant instead of large power plant concentrating in one area. The output of solar photovoltaic may change 70% within five to ten minutes due to local phenomenon like cloud passing. The vast land area requirement and the fluctuation of RE can be minimized by distributed RE generation [28]. Also each megawatt-hour of electricity generation by RES will reduce roughly one ton of GHG emission produced by coal or diesel generation [29], [30]. Low maintenance cost and adjustability with demand increase is some other advantages of this system [31].

The high investment cost of the RE power plant is also a barrier for the promotion of distributed RE generation [1]. The method to determine optimal HPS according to the demand of the premises and availability of resources in a location will help to reduce per unit energy cost of distributed RE generation. This work aims to contribute for the above requirement.

2.3 Hybrid Power System

HPS is the combination of more than one energy generators either conventional or nonconventional, including the storage devices and integration and control circuitry. A hybrid energy system with more than one RES and storage devices demands higher initial investment. Large rated RES are cheaper considering unit energy cost than smaller system. But system with more energy source enhances the reliability of the system and reduces the battery storage capacity since each RES is available at different times [32].

The distributed RE generation refers to decentralised RE power plant which may be HPS near to power users. It is more efficient compared to centralised power generators due to less T&D losses [7], [8]. The grid must be smart to accept the excess energy generated by distributed RE generators. The infrastructure must be strong and necessary protection circuitry is to be insisted by the authority to feed the excess energy to grid.

A brief review of the components of the proposed HPS is presented below. These are

1. PV module
2. Wind mill
3. Storage battery
4. Inverter with MPPT controllers

2.3.1 PV module

In PV cells the light and electromagnetic radiation of solar energy is directly converted into electrical energy by means of photovoltaic effect [33]. It is the generation of an electromotive force as a result of the absorption of ionizing radiation. It is also quiet, benign, and compatible with almost all environments [34].

PV cell can convert light into electricity but it cannot store the energy. So a storage device is required if the energy may not be able to be utilised at the time of generation. Otherwise the excess energy generated should be fed into utility grid [35].

There are different types of solar PV cells that can be considered. Amorphous silicon solar cells show very high absorption coefficient in the visible range. It requires only about a micron thick layer to absorb 90% of the solar spectrum. But its efficiency is less compared to mono and polycrystalline PV cells in comparison with area. Thin film module also has less efficiency. If the area is a limiting factor for installation of PV system amorphous or thin film PV cell cannot be proposed [36].

The poly crystalline PV cells are currently the best choice in term of quality and price. They have efficiency of 10-13% lower than the mono crystalline technology which has efficiency 15-22% but they are cheaper. Polycrystalline technology is commonly used in most of the PV system due to its low cost [29].

Solar cells are connected in parallel and series combination to form modules. These modules are hermetically sealed for protection against corrosion, moisture, pollution and weathering. A combination of suitable modules constitutes an array [28].

Buildings are the dominant users of electrical energy [37]. PV arrays can be installed on the roof top of houses or commercial buildings where the load is connected. This will reduce T&D loss since it is generated at load point [38].

2.3.2 Wind mill

In wind mill the kinetic energy due to the motion of wind is first converted into mechanical energy by wind turbines. The turbine consists of a number of sails, vanes or blades radiating from a hub or central axis which rotate when wind blows against them. This rotation motion is directly fed into an electric generator to produce electricity. A step up of speed of rotation is usually required to match the relatively slow speed of the wind rotor to the higher speed of an electric generator [7].

The well designed rotor of wind mill can decelerate the whole horizontal column of intercepted air to about one-third of its free velocity i.e., it can extract only about 70% of the theoretical maximum energy of wind. Losses incurred in the gear box, transmission system and electric generator could decrease overall wind turbine efficiency to 35% or less [7].

Wind turbines are broadly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VEWT). HAWT have their axis of rotation horizontal to the ground and almost parallel to the wind stream. In general, HAWT show relatively high power coefficient and low cut in wind speed and easy furling. However, the generator and gear box of these turbines are to be placed over the tower which makes the design more complex and expensive. Another disadvantage is need of tail or yaw drive to orient the turbine towards the wind. Depending upon the number of blades HAWT are further classified as single bladed, double bladed and multi bladed [39]-[40].

The axis of rotation of VAWT is vertical to the ground and almost perpendicular to the wind direction. The VAWT can receive wind from any direction. Hence complicated yaw devices can be eliminated. Also the generator and the gear box can be housed at the ground level. For this system, pitch control is not required when used for synchronous applications. The major disadvantage is that they are not self starting. Additional mechanisms may be required to push or start the turbine, once it is stopped. As the rotor complete a rotation the blades have to pass through aerodynamically dead zones which will result in lowering the system efficiency. Because of these drawbacks most of the present commercial turbines used for electricity generation are three bladed HAWT [41]-[43].

2.3.3 Storage battery

The batteries are used to store electrical energy so that appliances can be powered in the event there is no power from RES and when more power is needed than that can be provided by the RES at a given time [44]. HPS requires recharging of batteries so the focus is on secondary battery types.

Some of the secondary batteries are lead-acid, lithium-ion, nickel-cadmium, nickel-iron, nickel-metal-hydride, nickel-zinc, nickel-hydrogen and zinc-manganese dioxide. Though numerous rechargeable batteries exist, the most commonly used battery for RE applications is the deep-cycle lead-acid tubular battery. This is mainly because of the price to power ratio is superior. High availability, lowest self-discharge, capability of discharging at high rates and ease of manufacture are the factors accounting the wide use of the lead acid battery in many designs, sizes and system voltages. This is also a proven technology [44], [45].

The deep-cycle lead-acid battery has thicker lead plates which allow this type of battery to be discharged and recharged many times without degradation. One drawback of this type of battery is lower surface area between the lead plates and the acid electrolyte meaning small current per plate [44]. Though the deep-cycle lead-acid is designed to be discharged to 20% capacity, the battery will last longer. In the domain of deep-cycle lead-acid batteries there are three types of battery construction, flooded, gel, and absorbed glass mat (AGM) or valve regulated lead acid (VRLA). Flooded lead acids are the cheapest and most common. It uses aqueous electrolytes of 30% sulphuric acid and 70% water. This allows for spilling and evaporation of the electrolyte, which shortens lifetime. This type of battery consumes water for its operation. De-mineralized water should be added frequently to restore the electrolyte concentration. Proper ventilation is to be provided for oxygen and hydrogen removal [37], [44].

The gel type batteries use a thickening agent to hold the electrolyte in place. This prevents leakage in the event that the case is damaged. This type of battery is sealed, which means that in the event that a significant amount of electrolyte is evaporated, it cannot be re-filled [44].

AGM lead-acid batteries have much advantageous than the above two types of batteries. AGMs have Boron-Silicate fibres embedded in the electrolyte which prevents leakage even if the case is broken. In addition, this type of battery is sealed and pressurized forces hydrogen and oxygen to recombine into water while charging, thus greatly reducing water lost due to evaporation. A valve is provided in this type of batteries to allow the hydrogen evolution out of battery when the rate of hydrogen evolution becomes dangerously high in battery which can cause explosion. They have a very slow self-discharge rate and are resistant to shock and vibration damage. They provide high power density also. The main disadvantage of AGM is they usually cost two to three times that of a flooded lead-acid of the same capacity [37], [44].

Now flooded, gel and VRLA solar tubular lead acid batteries are available in the market which has long life time of 1500cycles to 80% depth of discharge (DOD), 3000cycles to 50% DOD and 5000cycles to 20% DOD.

In this work the batteries have three stages which can be checked by the algorithm and reacted according to the availability of output power from RES and the demand at each time period. These three stages are [6]

Charging state of battery : Power generated by the HPS is primarily utilised to meet the demand. If there is excess generation even after meeting the demand, excess energy will be stored in batteries to use at shortage or during peak hours. This is charging state of battery where the MPPT algorithms will be most relevant. Here the maximum power point is determined and the battery is charged accordingly.

Discharging state of battery : The battery is discharged to meet the demand when the battery SOC is higher than the minimum value and the HPS power output is scarce to meet the demand or the grid energy cost is high at peak hours. This is the discharging state of battery.

Float or idle state of battery : Once the battery is fully charged or there is no or little excess power from HPS the battery is at float state.

In this work, flooded solar lead acid tubular batteries are taken as storage device in view of lowest cost and longest life time.

2.3.4 Inverter with MPPT controller

The power obtained from solar and wind is in the form of DC and inverter is required to convert the DC power to AC power to meet the load. Inverter also converts DC power stored in the batteries to AC power to operate the appliances if there is shortage of power from RES. It is also important that the inverter has a user interface that is easy to use and that no extensive knowledge of the equipment is needed to operate it safely [44].

It should be power efficient so that the energy generated in the system is utilized to the fullest in the most efficient way possible. The main function of the inverter is to take a continuous flow of current from a power source, increases its voltage, and then to change it to an AC source before sending it out to power a device [44].

AC power output from a very good inverter should be smooth sine wave. Cleaning up the square waveform to accomplish a smoother sine wave requires a series of filters, inductors and capacitors which enhances the cost of inverter. The expensive inverters can virtually produce an even smoother sine wave than the one coming out from a utility company. Inexpensive inverters have little or no filtering which may be square wave as AC power output. Intermediate inverter output is a modified sine wave. Intermediate sine wave inverters are taken as part of HPS in this work which can be used to power up regular loads used at buildings [44].

The amount of energy extracted from solar or wind generator for a given solar irradiance or wind speed respectively depends on the equivalent load connected to these generators. As load impedance vary from infinity to zero ohms, the extracted energy starts from zero value to a maximum value and drops to zero. To extract maximum power under a given environmental condition the equivalent impedance seen from the source has to be varied so that maximum of available energy is always extracted. A MPPT controller is used for this purpose. The MPPT for both solar and wind are connected to RES to extract maximum power. Each MPPT is an electronic DC to DC converter which delivers maximum possible power to the load or grid through inverter from RES for a given wind speed or solar irradiance. The DC to DC converter is operated based on MPPT algorithm by adjusting the effective impedance looking into the load or grid [44], [46], [47]. The inverter proposed in this work is equipped with MPPT controllers.

2.4 Smart Grid

As mentioned in 2.2 there are technical challenges to integrate RES which generate energy intermittent in nature with the grid. In order to be cost effective it may require a grid design with features like energy storage device, intelligent metering and communication facility. A smart grid is an umbrella term encompassing HPS and communication technology with smart metering. The smart grid is an electric power grid that attempts to intelligently respond to all the components with which it is interconnected including suppliers and consumers, in order to deliver electric power service efficiently, reliably, economically and sustainably. The main part of smart grid are advanced metering infrastructure (AMI), distribution automation (DA), distributed generation (DG), substation automation (SA), FACTs and demand response (DR) [48].

Smart grid is the next generation power network that integrates information and communication technology into electric transmission and distribution networks for control and data collection. One of the main smart grid visions is the distributed generation by RES at load point for energy independence, reduction of peak demand and greenhouse gas emission. Smart grid delivers electricity from suppliers to consumers using digital technology with two-way communication to control appliances at consumers' homes to save energy, reduce cost and increase reliability and transparency. There will be a data management system and dynamic system control at supplier operation point and automatic switching and fault detecting equipment at different locations of transmission and distribution network. Smart grid also incorporates the use of super conductive transmission lines for less power loss [49]-[52].

2.4.1 Functions of smart grid

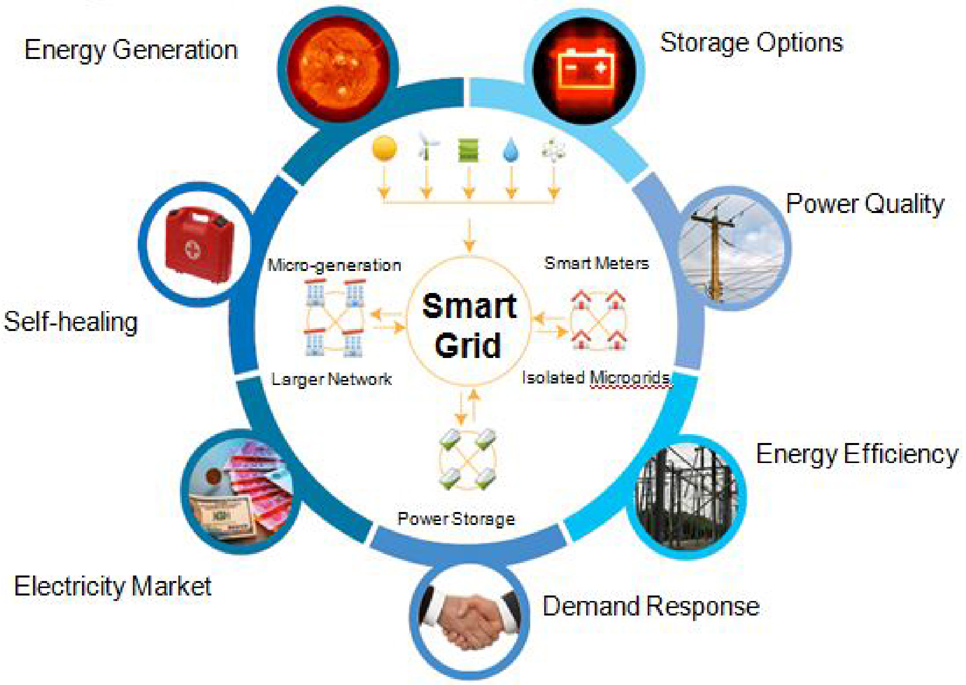


Fig. 2.1 Functions of smart grid [57]

Smart meter is heart of smart grid for demand side management and providing data for the consumer to interact with electricity market for reducing peak load and electricity price. In pilot projects isolated micro grids are constructed to evaluate the performance of advanced metering infrastructure and cost benefit analysis. In future these micro grids will be connected to the smart grid. The power storage is one of the benefits of smart grid for peak load shaving and improving the power quality. This is to be connected to smart grid with controllers to supply energy when there is shortage and store energy when there is excess generation by distributed RES.

Micro generators like roof top RE power plant, small hydro, small bio mass, diesel generators are connected to large network of load are also integrated with smart grid. Large generators both conventional and non conventional like nuclear, thermal, hydro, biomass, wind and solar are interconnected to smart grid to provide electrical energy according to the demand of grid. Smart grid demands power quality, energy efficiency, demand response, market based pricing, self healing, distributed RE generation and storage options. Equipments connected to grid are automatically controlled by sensors and controllers using information and communication technology to achieve the above seven benefits is the key requirement of smart grid [52]-[57]. The functions of smart grid is symbolised in Fig. 2.1.

2.4.2 Potential benefits of smart grid

The smart grid presents a wide range of potential benefits. A modernized electricity network with distributed RE generation is being promoted by many governments as a way of addressing energy independence, global warming and emergency resilience issues. The smart grid can be considered as a modern electric power grid infrastructure for enhanced efficiency and reliability through automated control, with modern communication infrastructure, sensing and metering equipments and modern energy management techniques based on the optimization of demand. A smart grid includes an intelligent monitoring system that keeps track of all electricity flowing in the system [52]-[54].

Demand side management (DSM) and distributed energy storage are the vital advantages of smart grid. Use of low consumption lights such as light emitting diode (LED) or compact fluorescent lamp (CFL) and 5 star certified appliances will reduce the load on the network. In conventional system, cost to serve the peak demand is much greater than the average cost over the year since power plants operated for few times a year is to be maintained to meet the peak load. Smart grid automatically controls the peak load to make the load curve flatten by demand side management. Demand side management also reduces the energy cost of consumer by turning on selected home appliances that can run arbitrary when power is least expensive and turning off at peak times to reduce energy cost and demand. It also utilises the distributed stored energy from RES at peak hours [53]-[56]. Model of a smart building is shown in Fig. 2.2.

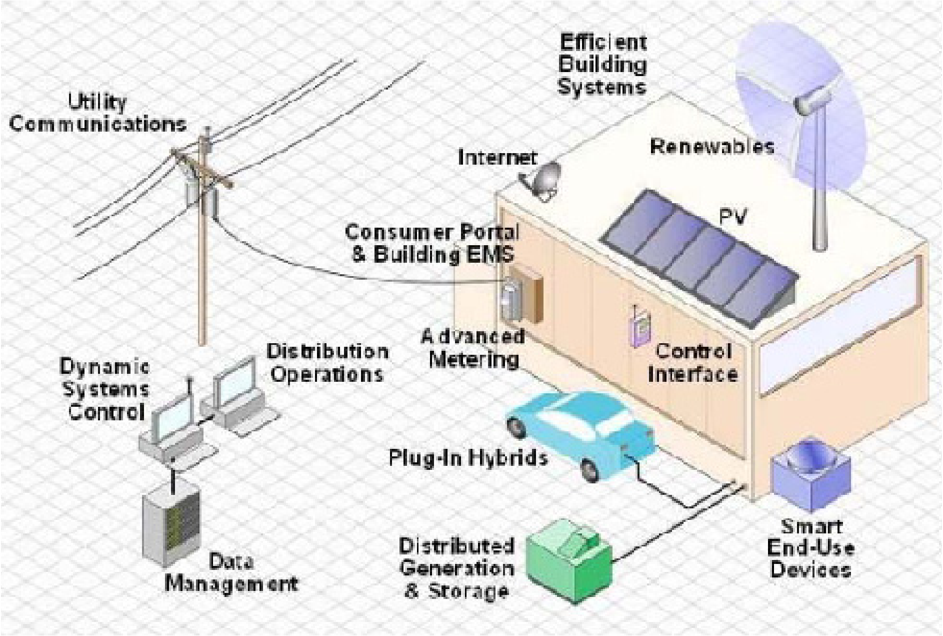


Fig. 2.2 Model of a smart building [58]

The distribution system will be transformed from a passive to an active grid with the integration of consumer and utility resources when smart grid vision is implemented. Premises should have RES and storage devices that interface to the smart grid via power electronics based inverters. Utilities are expected to invest in the modernization of the distribution grid by installing distributed generation resources, storage systems, dynamic voltage ampere reactive support systems, automatic re-closers, switches, etc. All these resources have to be optimally and autonomously coordinated, in order to achieve optimal system level operation which will be secure and environmental friendly. Minimized losses, peak demand reduction, and reliability improvement will be the financial benefits for the utilities [59].

The other potential benefits are [27]-[28], [49]-[54]

- Optimizing the value of existing production and transmission capacity
- Enabling improvements in energy efficiency
- Reducing carbon emissions by increasing RE generation
- Improving power quality
- Improving a utility's operational performance, asset management and overall productivity
- Enabling informed participation by consumers by empowering them to manage their energy usage to reduce energy cost and peak consumption
- Reducing peak consumption which strengthen the grid and generating station
- Reducing aggregate technical and commercial (AT&C) losses which in effect reduce the energy cost
- Accessibility of electrical energy in remote areas
- Helping faster restoration of the grid in case of faults or disturbances
- Removing voltage stabilizers, inverters and other standby power arrangements from premises due to the availability of uninterrupted quality power which earn the investment for such equipment
- Promoting energy independence

2.4.3 Smart meter

Automatic meter reading (AMR) device is automatic electronic meter that records consumption of electrical energy and communicates to utility for monitoring and billing purposes. It is a device that communicates both with the utility and with the consumer [55]. These include partially manual techniques such as local series interface and infrared and fully automatic techniques like distribution management programme using telephone lines or power line carrier for bidirectional reading and control. It records consumption in detail and send consumption pattern back to the utility so that the information can be used to benefit the consumer. The communication in two ways may be carried out by internet or other means as decided by the supplier when it becomes affordable and easily available. Most aspects of the smart grid is not actually a new idea. It is a transition from conventional grid to fully automatic grid [48]. While regular meters monitor general consumption during the day, smart meters can mark the time in which a consumer uses more electricity. This can help regulatory bodies introduce time of the day pricing, higher rates during peak hours and lower during non-peak hours. The commercial loss can be reduced to a large extend by providing AMR by the reduction in losses due to theft [55].

Advanced Metering Infrastructure (AMI) will have all the facilities of AMR. It also has the facility of monitoring, analysing and processing data available both from consumer end and utility end. It includes hardware, software, communications, consumer energy displays and controllers, consumer associated systems, meter data management software and supplier business systems. It will have the facility of automatic control of equipments at consumer end for demand side management. The network between the measurement devices and business systems allows collection and distribution of information to customers, suppliers, and service providers. Consumers can use information provided by the system to change their normal consumption patterns to take advantage of lower prices. The load curve can be flattened and healthy business in power sector can be promoted by providing AMI which benefit both consumer and supplier [48]. In this work AMR facility of smart meter is only taken into account, to determine energy cost by recording hourly bi-direction energy flow and to analyse the peak demand reduction. Demand response is not in the scope of this work.

2.4.4 Challenges of smart grid implementation

In India 56 million households are not connected to grid and about 25782 villages are un-electrified as on 31st July 2014 [60]. The electrified households are also affected by load shedding and interruption due to lake of generation and weak electrical network. Quality supply to all households will be solved only by vast infrastructure development, renovation of existing grid, distributed RE generation and peak load shaving [15], [61], [62]. T&D losses are very high in undeveloped and developing countries due to weak grid. In developing countries like India the T&D losses are about more than 25%. India aims to reduce the T&D loss to 19% in the 12th plan i.e., before 2017. In 13th and 14th plan it is aimed to reduce the losses to 15.5% and 13% respectively as smart grid vision [62]. Communication infrastructure, sensor systems both for smart premises and grid, advanced components, software development, control methods and decision supports are to be achieved in technological development [63]. Smart grid implementation is a complex activity and a long process. Many issues and challenges need to be addressed at the implementation stage which could not be precisely forecasted. The main challenges of smart grid are technical development, quality power to all households, reduction of T&D

losses, RE integration, inter operability and cyber security and consumer support [61]-[68].

Now each country develops its own standards for interoperability and cyber security. Internationally accepted standards are to be implemented by all countries involved in the smart grid implementation to make the power grid a global grid [69], [70]. Consumer support is a must for peak consumption reduction, promotion of distributed RE generation, selection of source of power, load shifting for reducing energy cost and improvement in quality and reliability of power supply. The smart grid is a need of the society in the current scenario to meet the increasing demand by the implementation of distributed RE generation and to ensure energy security for all households.

2.5 Standalone Hybrid Power System

A brief review of the functions of smart grid and smart grid implementation are reviewed in section 2.4. In this section the published works of standalone HPS are discussed. In earlier period RES were cost effective only for remote villages and equipments in view of the high investment cost for grid connectivity. The stand alone systems also have wide acceptance in educational institutions and commercial buildings as a source of green energy.

Most of optimization and economic feasibility studies of HPS are carried out for stand-alone or grid independent application for the use of rural areas and remote villages. Different combinations of stand-alone HPS have been modelled and analyzed to evaluate the cost effectiveness of the system or to determine minimum loss of load probability models [10]-[12], [38], [71]-[104]. Storage devices like battery and electrolyser with fuel cell and conventional energy generation equipments like diesel generator are combined with RES in stand-alone HPS for minimal interruption. PV module and wind mill are taken as RES in most of the proposed works due to their wide acceptance as alternative source of electrical energy [10]-[12], [38], [71]-[104]. Easy availability of solar and wind with advanced technologies also promotes their usage. The excess energy generated will be stored in storage devices to utilise at the time of shortage. Some of the earlier works on stand-alone HPS are discussed here.

The fuel consumption of supporting fossil fuel generator is one of the decision variables since it is included in the life cycle cost [10]-[12], [38], [71]-[72], [75]-[76], [79], [83]-[85], [104]. The other optimization objective was minimal loss of load probability with zero critical load rejection [11], [74]-[75], [78]-[79]. The individual RES stand alone systems and diesel generator system were compared with HPS to determine recommended configuration in a desired location for least energy cost or system cost [71]-[73], [76]-[78]. Biomass, biogas and small hydro power plants were also taken as RES in some HPS studies [38], [83]-[89].

A HPS is proposed to evaluate the behaviour of the system over a long period of time [12]. The components of HPS were modelled for conventional grid tied electrification of cluster of villages in [38]. HPS consists of micro hydro generator, biogas generator, biomass generator and diesel generator are optimized for cost effective system sizing. The algorithm presented is capable of efficiently designing a least cost village electrification system while the diesel generator keeps the output constant with high efficiency in spite of the fluctuating PV power. The results were obtained for the specific parameters which can vary for individual consumers. The least cost system is the stand alone micro hydro generation system and most expensive is the stand alone PV battery system in the study.

Economic analysis for different configurations of fuel cell was carried out for stand-alone PV hybrid system. Fuel cell (FC) with battery for external hydrogen supply and internal hydrogen generation respectively were optimized for minimum cost. These two models were compared with fuel cell with internal hydrogen generation without battery for cost effectiveness. The study revealed that fuel cell with battery and external hydrogen supply is the most suitable configuration which is a real alternative to the classical PV, battery and diesel generation [77]. Optimal HPS for specific remote locations is determined in some papers with PV module and wind mill as RES [80]-[82], [102]-[104].

The Break even line extension distance (BELED) of grid was found out for rural villages where grid supply had not been reached. In one case study the costs of powering a rural primary health centre in India with decentralised RES was estimated and compared with the cost of the electrification from the national grid. Per kilometre (km) rate of grid extension to rural area was varying in between $8000 and $10000. It can increase to as much as $22000 for difficult terrains. In this study the cost of grid extension was taken as $8000 and compared with the cost of hydrogen based fuel cell comprising decentralised RE system considering capital and maintenance cost in both cases. BELED for grid extension was calculated [86].

Power management of a hybrid wind / PV / FC alternative energy system for stand-alone application was proposed in [90]. The system performance under different scenarios had been also verified using a practical load demand profile and real weather data in this study.

Unit sizing and economic analysis were performed for a stand-alone wind /PV system with FC/ electrolyser system and wind/PV system with lead acid battery storage in [91]. Studies on the cost of electricity, the overall system cost and BELED were also carried out. The study revealed that lead acid battery storage is the better choice for energy storage.

In [92], economic analysis and environmental impact of integrating a PV system into diesel-battery system for remote villages were studied for a particular case of Lime village, Alaska. The study was conducted for diesel only, diesel-battery and PV with diesel battery for one year time period. Environment impact has been calculated by determining the CO_2, particulate matter (PM) and NO_X emitted to the atmosphere. The integration of PV array into diesel-battery stand alone HPS reduces the operating cost and the CO_2, PM and NO_X emission [92].

A generalised optimization model of HPS for remote rural areas in Indian condition was developed with battery storage and diesel generator as back up source. The criterion for selecting the best HPS is based on the trade off between reliability, cost and minimum use of diesel generator set. The component sizes are restricted to that available in the village. A case study was conducted in a rural village in Western Ghats at Kerala, India. A micro-hydro / wind HPS without conventional diesel generator was found to be the optimal combination at the unit cost of Rs. 6.5/KWh [93].

Energy flow of a hybrid wind/PV/fuel cell generation system was managed by employing fuzzy logic control to achieve MPPT and to deliver this maximum power to a fixed dc voltage bus. Simulation was carried out for two seasons and proved the accuracy of fuzzy logic system [94].

Dynamic simulation model of a hydrogen based PV/wind energy system was developed. General performance of developed simulation model was evaluated using the SOC control method. The results of the simulation were validated with the previous experimental measurements of Hydrogen Research Institute Test Bench [95].

The PV/wind stand-alone hybrid system was optimized using improved differential evolution algorithm and partial swam optimization in [96] and [97] respectively.

Energy efficient stand alone distributed generating system for rural Alaska village was developed including all available resources in the area. This included wind, solar, small head and river hydro, thermoelectric generators, micro turbine technology, thermoelectric system battery and other storage devices combined with the existing diesel/electric generators. The most efficient option for the particular location was obtained in the study [98].

In one of the study, Stand-alone PV panels with fuel cell and ultra capacitor as storage devices were designed and modelled for analysing any combination of such type of HPS [99]. PV, wind hybrid stand-alone energy system for rural electrification is optimized and analysed. The result showed that hybrid system is more economical than stand-alone PV or wind system [100].

Optimization models are developed for stand-alone PV with fuel cell and battery as storage device in [101]. The system behaviour is studied. Stand-alone hybrid wind PV power system is optimized using genetic algorithm and analysed the convergence of methodology [78], [102]. The optimal HPS system is analysed in real time to study the performance of the system in different case studies in [105]. Stand alone system is designed for meeting the full load of the premises with diesel generator as back up source and battery as storage device in [106]. In [107] optimal capacity of solar water heater and FC with PV module is obtained for residential buildings.

2.6 Conventional Grid Tied Hybrid Power System

Large RE power plants integrated to grid were promoted by providing government aids and subsidies to generate green energy, reduce green gas emission and protect the environment in last decades. Large amount of RE penetration to the grid affects synchronous stability of power system [108]. Penetration level of RE in power system can be increased by energy storage [109]. Drastic reduction in capital investment cost of RES especially PV module and wind mill in last few years has given wide acceptance of those systems to meet the demand.

In developing countries like India the infrastructure for electrical energy transmission and distribution is overloaded in many locations. The grid codes for on grid system installation are only in the draft stage in many states [110]. The grid is to be strengthened to accept the distributed RE. So RES connected to single directional grid is only allowed in such countries for RE generation on the grid connected buildings.

Optimization studies have also been conducted in grid connected HPS. But in some studies, the excess energy generated by the HPS of the premises can be fed into the grid and also can draw power from the grid when there is shortage i.e., these are smart grid tied HPS. If the grid is not healthier to accept the distributed RE generation or the utility is not permitting to feed energy from the premises to grid, the grid connected HPS will be conventional grid tied

HPS. The grid is single directional and a storage device will also be a part of HPS to store excess energy generated by RES. Some of conventional grid tied HPS studies are discussed here.

The feasible stand alone and grid connected hybrid energy system with hydrogen energy was developed. The calculations were performed hourly. The evaluation showed that grid connected HPS had higher probability of adaptation than the stand alone configuration [31].

In [32], grid connected hybrid PV-wind system is optimized using dynamic programming for minimizing the electricity production cost and minimizing the power purchased from the grid without battery to meet the desired consumption to determine whether the wind-grid system, PV-grid system or HPS is more optimal. Optimal sizing of HPS is determined considering one day data of solar irradiance, wind speed and load and excess energy generated as dump load. This study reveals that wind – grid system is the most economical for the sample site condition.

In [111], fuel cell with electrolyser is used as storage device to store the excess energy generated by PV and wind mill system. Different system combinations like grid connected PV, PV with fuel cell, wind mill, windmill-PV, wind mill with fuel cell and wind mill and PV with fuel cell were analysed to determine economic feasibility of the systems.

Peak load management of industrial loads using RES from independent power producers (IPP) is an attempt to determine the reduction of peak load and energy cost of different types industries by the use of RES [112]. Optimal utilization of RE for industrial load management for reducing peak load and electricity charge using non-linear programming technique was conducted in this paper. The case study was carried out in twenty two large scale industries. The result of 34% reduction in peak demand and about 14% reduction in electricity cost was achieved by the optimal utilization of the RE purchased from IPP. Small hydro power plant, biomass and wind power were considered as RES of IPP [112].

In all these studies of grid connected HPS, the excess energy generated by RES was stored in storage devices or considered as dump load or neglected. If storage device was taken as a part of HPS, the stored energy can be utilised at peak hours to reduce peak consumption from the grid. The reduction of peak demand is very beneficial for both grid and utility. The grid become stable and utility can reduce the investment for conventional generators to meet the peak demand. The generators efficiency can also be improved due to peak load shaving. This benefit may be contributed to producers of RE with respect to peak load reduction. This is termed as PEC. The effect of PEC is analysed in this work in the modelling of conventional grid tied HPS by utilizing the stored energy in the battery for peak demand reduction.

2.7 Smart Grid Tied Hybrid Power System

The low efficiency and short life span of storage devices are the major bottle necks of the project implementation of the RES connected to single directional grid. This can be overcome by strengthening the grid to make it a smart grid to accept the excess energy generated by the distributed RE generation. The grid tied inverters are provided to interconnect RES and grid. The energy produced in RES is fed directly to grid and demand of the premises is met from the grid.

In the new scenario of smart grid and liberalized energy market, the grid connected two way energy transactions for distributed energy generation using roof top PV panels and wind generators is widely accepted. The grid should be smart to accommodate the distributed energy generation. The excess energy generated in smart premise, if any is fed into the grid. The smart premises consume energy either from its own generation or from the grid [54]. Then the consumer becomes ‘prosumer’ i.e., premises produce and consume energy [29]. The grid must be dual directional to accept the energy from HPS.

Now some of the current works in grid connected HPS for energy management and optimization for economic exploitation are reviewed here.

An energy system for green building that consists of RES, energy storage and smart energy management were designed and tested. The control strategies for the green building energy system by computer simulation were studied. Results show that the control system manages the energy system very well [29].

In the studies of HPS in smart grid applications, energy management tools were developed as two parts, one is central and the other is customer side energy management. The power planning was designed according to the prediction of PV power production and load forecasting. Hybrid super capacitor battery based PV active generator was used for the study [113]. This work was focussed on development of energy management software.

In [114], economic viability of grid connected PV system at different locations in Bangladesh for a proposed 1MW PV system was calculated. The authors used RET Screen simulation software for analysis.

The integration of RES may affect power quality due to its stochastic nature. The power quality includes harmonics and fluctuation of the grid voltage and frequency. It also affects the synchronous stability of power system [108], [115]. Feeding of fluctuated power due to uncertain and intermittent nature of RE especially solar and wind makes grid management harder [116]. Some authors emphasise the requirement of limiting the penetration of RE to the grid [29], [117], [118].

The maximum penetration of passive PV generators in European island networks is 30% [29]. In [117] optimal mixture of PV, wind and wave power into the utility grid in large scale integration was identified in technical point of view. Wind power generation should be 50% of the total RES generation. The total amount of electricity production from RES will determine the mixture between PV and wave power. When the total RES input is below 20% of demand PV should cover 40% and wave power only 10%. When the total input is above 80% of demand, PV should cover 20% and wave power 30%. In this work the penetration of RE into grid is limited at normal and off peak hours in view of demand of the premises at these hours for both smart grid tied and smart grid tied with storage system.

2.8 Smart Grid Tied Hybrid Power System with Storage

The power generated by RES cannot be utilised effectively even though it is fed into smart grid since the generation may not be in peak hours. The energy generated by RES at off peak and normal hours may be loss if there is no storage device. The smart grid tied RES with storage device may solve the loss of excess power generated by RES at off and normal hours. But the cost of storage device and increase in cost of inverter may affect the commercial feasibility of the system.

The fast developing technologies overcome many issues related to integration. There are many ongoing projects for the solution of the problems in connection with RE integration [64]. Penetration level of RE in power system can be increased by energy storage [109]. The distributed storage of RE is a method to improve the quality of power in a grid. This is also part of smart grid vision. The stored energy can be utilised for peak load shaving to improve the reliability of power system and reduce energy cost [54]. Generation and grid capacity of a power system should be greater than peak demand. Average utilization of generation and grid capacity is reduced with increase in variation of peak and off peak demand. Reduction in peak demand assures increase in usage of available grid and generation capacity [119], [120].

Few works in grid tied HPS with storage devices were already carried out. These are discussed here.

Fuel cell with electrolyser operation is controlled as energy absorbed at low demand period and stored as hydrogen energy and it is injected back to the grid at peak hours for peak load shaving. Reduction of overall operation cost of fuel cell is the aim of optimization of a grid connected hydrogen based PV-wind mill HPS for zero energy annual balance with peak load shaving, reactive power control and back up service. The characteristics of system are defined for zero energy building and optimization algorithm seeks the calculation of the optimal SOC of the electric storage system [121].

There are many recent studies in energy management of distributed RE generation in smart premises with storage [37], [109], [116], [122-126]. Building energy management system for addressing randomness and uncertainties of load and RE to reduce consumption of the building from grid is done by quadratic programming [37]. Two scale dynamic programming for wind – battery HPS and predictive control system based on dynamic programming for PV - battery HPS are proposed in [116] and [118] respectively for energy management.

In another paper stochastic optimization problem is solved to minimize cost of energy from grid with real time electricity pricing [122]. Optimal energy management includes economic despatch, unit commitment and demand side management. These are included for the energy management of residential and micro-grids respectively in [123] and [124]. Genetic algorithm is applied for optimal power scheduling in [125] and [126].

2.9 Conclusion

In this chapter the previous works in the proposed area are discussed. Most of the optimization works of RE are carried out in stand-alone systems. Minimizing the energy purchased from the grid, economic feasibility of HPS with storage device such as fuel cell with electrolyser and peak load management by purchasing power from IPP are the related previous works in conventional grid tied systems. Development of controllers for green building, energy management studies and large RE power plant optimal integration are studied in smart grid tied HPS. Reduction of overall operation cost of fuel cell is taken as optimization parameter in a zero energy building in smart grid tied HPS with storage. Energy management studies, power scheduling and demand side management are the other works proposed in this system. Economic viability of conventional grid tied, smart grid tied and smart grid tied with storage HPS are analysed by developing each system model. The ageing of RES is considered in the system modelling. Algorithm is developed taken into account the constraints appropriate for each configuration. The remarkable constraints to limit the RE to grid at off peak and normal hours and to ensure minimum RE generation and maximum peak demand reduction are taken in the problem formulation. Optimal system for each configuration is found out considering economical and technical factors in the proposed work.

Chapter 3

Modelling of Hybrid Power System Components

3.1 Introduction

To analyse the optimal operation of the power system with distributed RES, it is required to make a mathematical model of energy generation of each component based on environmental condition on which different components are operating and cost of installation and maintenance of each component. The first one of this is called technical model by which the energy available based on environmental conditions is modelled by taking into account one year solar irradiance data, PV cell temperature and wind speed of desired location with one hour duration. The other model is called commercial model which is based on cost of installation, maintenance and salvage values of each components. This chapter describes a typical system taken for the study and method of formulating technical and commercial models of each component of proposed HPS.

3.2 System Considered for Analysis

The details of the system considered for analysis is shown in Fig. 3.1where arrows represent direction of energy flow.

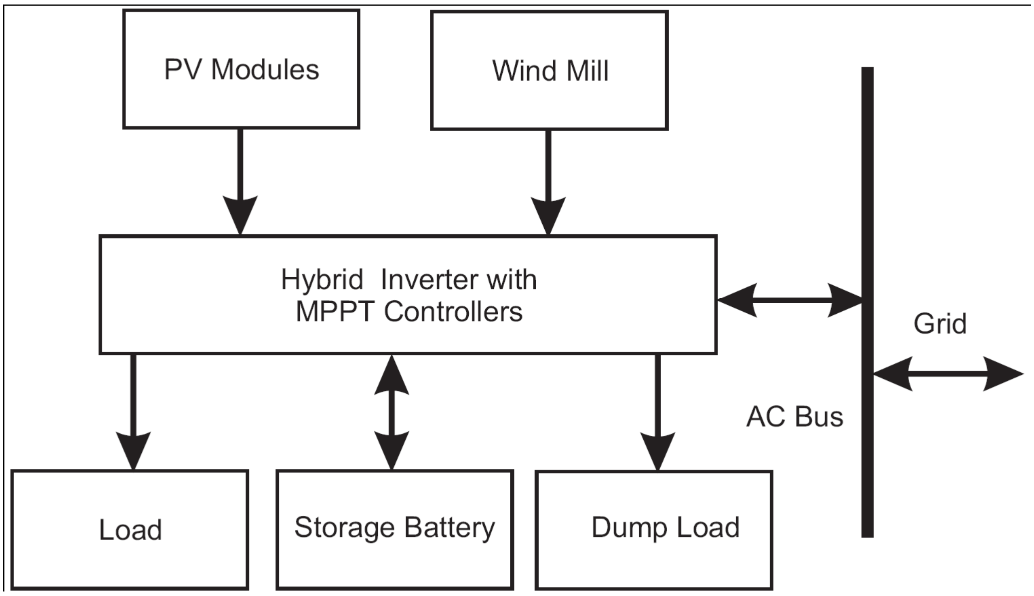


Fig. 3.1 General block diagram of proposed hybrid power system

This consists of PV module, wind mill, storage battery and inverter with MPPT controllers. In certain situation a dump load is provided indicating that generation is larger than the demand during certain duration and energy instead of pumping to the grid has to be dissipated as dump load. The direction of energy flow from HPS to grid may be single directional or bidirectional according to the configuration.

3.3 PV Module

3.3.1 Technical modelling of PV module

The PV module output power for a given module area is dependent on the irradiance obtained on the surface of PV cell and temperature of PV cell. The irradiance received on earth is measured as global horizontal irradiance, global tilt irradiance, direct normal irradiance and diffuse irradiance. Global horizontal irradiance is the irradiance received on a point in a horizontal plane. This is the sum of direct normal irradiance multiplied by cos(θ) where θ is the solar zenith angle and diffuse horizontal irradiance [35]. The PV modules are normally set at an angle according to the latitude and longitude of the location to extract maximum power from the sun in a whole year. The irradiance obtained at a tilted PV module is termed as global tilt irradiance.

If the array is in face with the sun's rays at any time the power output can increase by 30%. But to track the sun there must be a tracking device called mechanical MPPT. This is a fitting device driven by microprocessor controlled motor and requires routine maintenance [7]. Mechanical MPPT in all direction which tilt the PV module according to the position of sun will be the most promising solution to extract maximum power from the solar light using PV module. The irradiance obtained in that PV module is direct normal irradiance [128].

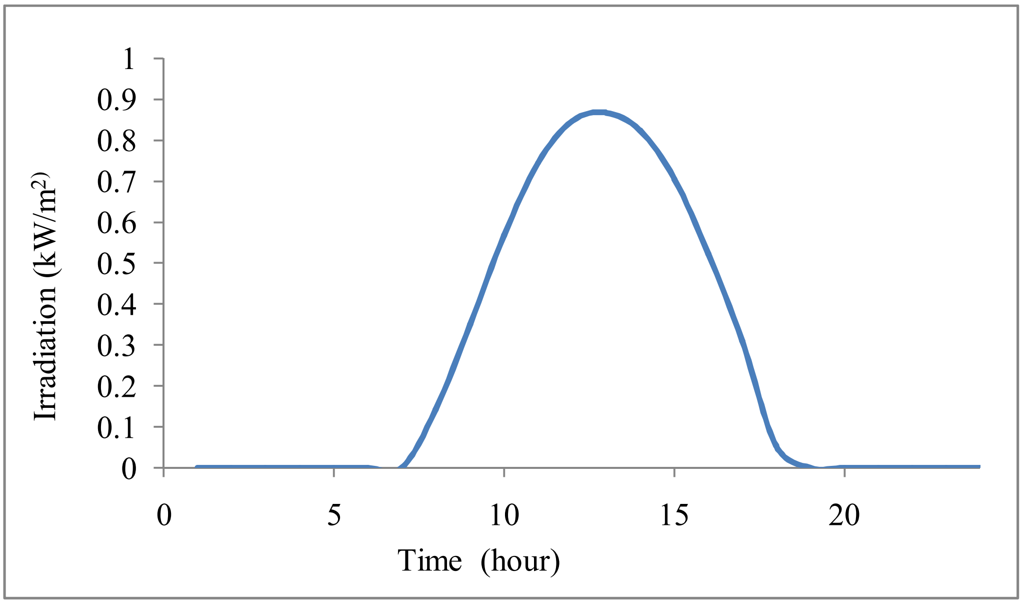


Fig. 3.2 Hourly solar irradiance of a typical day at location 1

The mechanical MPPT is not widely used for roof top solar power plants due to its cost and difficulty of maintenance. In this work PV module output power model is developed from hourly global horizontal irradiance in a location to account the absence of mechanical MPPT. The diffused horizontal irradiance is also absorbed PV modules from the atmosphere [128]. The hourly solar irradiance on a typical day at a particular location without clouds is shown in Fig. 3.2 which shows that solar radiation begins to increase around 6am reaches peak value around 1 pm and this decreases reaching zero around 7pm.

The output power from PV module is reduced with the increase in temperature of PV cell. The drop in power is expressed in terms of temperature coefficient of power of PV cell (T_{cp}) in %/^{o}C. As temperature of PV cell increases, the power output is reduced.

Rated output power ($Ps_{\kappa i}$) of i kW rating of PV module is obtained at standard test condition (STC) of 1kW/m^2 irradiance, at cell temperature of 25^{o}C and air mass of 1.5. PV module output power at time t (Ps_{t_i}) is reduced with each ^{o}C increase in temperature of cell of PV module from 25 ^{o}C as module temperature coefficients (T_{cp}) of power. The relation is developed based on [129].

$$Ps_{t_i} = Ps_{\kappa i}\left[1-(T_t-25)*T_{cp}\right]*\aleph_t \tag{3.1}$$

Where T_t is the cell temperature in ^{o}C at time t and $\aleph_t$ is the ratio of global horizontal irradiance in W/m^2 and irradiance at STC in W/m^2 at time t.

The energy reduction due to aging of PV module is also to be considered in the model. PV module output power generation per year is reduced by one percentage as per the design. This characteristic is taken into account in PV module output power modelling to develop long term technical model. The developed technical model for the life span is expressed as below.

$$Ps_{t_i} = Ps_{\kappa i}\left[1-(T_t-25)*T_{cp}\right]*\aleph_t*\frac{\omega}{2}*\left[2-(\omega-1)*\eta_s\right] \qquad (3.2)$$

Where η_s is the efficiency reduction per year of PV module due to ageing and ω is the life span of the project.

3.3.2 Commercial modelling of PV module

The commercial modelling of PV cell is based on i) Initial capital investment (ICC) ii) Operation and maintenance (O&M) cost iii) Insurance charge and iv) Salvage value of PV cell at the end of life time of the project. All these components vary widely from place to place and year to year. For the purpose of this work reasonable values are taken at location considered for the work.

Consider a PV module rated i kW. C_{s_i} is PV module net investment for *i* kW which is expressed as

$$C_{s_i} = A_{1s_i} + A_{2s_i} + A_{3s_i} - A_{4s_i} \qquad (3.3)$$

Where A_{1s_i} is ICC of PV module, A_{2s_i} is life time O&M cost, A_{3s_i} is life time insurance charge and A_{4s_i} is the salvage value at the end of project of *i* kW PV modules. Life time O&M cost and insurance charges are determined considering escalation rate(g) and interest rate evolution(h). Salvage value at the end of the project is found out with general inflation rate(q) and h [78]. Section 3.7 explains methods to determine each of these components. There is no replacement of PV module in the life span of the project. Capital recovery factor (CRF) is applied to all cost since the return of investment is monthly.

The ICC of PV module taken for analysis in various published works is tabulated in Table A1 of Appendix A. The ICC of 1kW PV module varies from 1660$ [9] to 6500$ [74] in the published works. The O&M cost is considered only in some works. This varies from 0.5% [9] to 20% [72] of ICC per year. Installation cost is taken into account in one work which is 10% of ICC [10]. Since a standard rate for ICC cannot be determined from the literature, the present market rate of the component is taken for analysis in this work.

It is observed that market value of PV module is decreasing day by day [2]. During 2013 the market value of PV module per kW varied from 500$ to 1000$ in international market [130], [131]. Transportation charge, taxes, duties, labour charge, establishment charges and profit of the supplier are to be included in the whole sale rate to determine the cost of product at consumer end.

Making a simplified assumption that net investment cost C_{s_i} is proportional to the rating of PV modules. It can be expressed as

$$C_{s_i} = \chi_s * i \tag{3.4}$$

Where χ_s is the net investment cost of 1kW PV module and i is the rating PV module in kW.

3.4 Wind Mill

The power available from a wind generator depends on the instantaneous wind speed within a cut in and cut out range. If the wind speed is below a value called cut in wind speed, there is no energy generation and if the wind speed above certain value cut out wind speed, energy generation clamped at zero value by stopping the turbine blades.

3.4.1 Technical modelling of wind mill

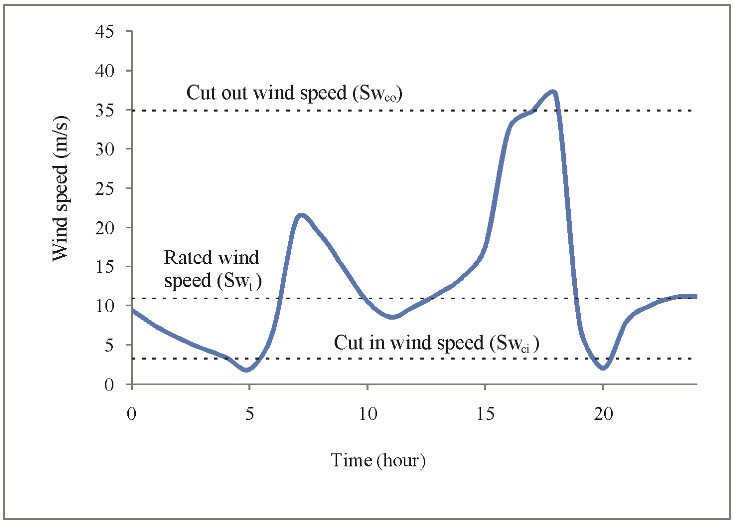


Fig. 3.3 Typical hourly wind speed showing cut in, rated and cut out wind speed

The wind mill output power is determined from wind speed and in a given location the wind speed varies with height. Usually wind speed is assessed at a given height. Based on this assessment the wind speed at a different height can be estimated by [80].

$$Sw_t = Sw_{zt} * \left(\frac{H_\nabla}{H_z} \right)^f \tag{3.5}$$

Where Sw_t is the wind speed at desired height H_∇ at time t, Sw_{zt} is the wind speed at measured height H_z at time t and f is surface porosity coefficient. Then wind mill output power $\left(Pw_{t_j} \right)$ at time t and wind mill rating j in kW can be determined by

$$\left.\begin{aligned} Pw_{t_j} &= 0 \text{ when } Sw_t < Sw_{ci} \; or \; Sw_t > Sw_{co} \\ &= Pw_{\kappa j}\frac{Sw_t - Sw_{ci}}{Sw_\kappa - Sw_{ci}} \text{ when } Sw_{ci} \le Sw_t < Sw_\kappa \\ &= Pw_{\kappa j} \text{ when } Sw_\kappa \le Sw_t \le Sw_{co} \end{aligned}\right\} \tag{3.6}$$

$Pw_{\kappa j}$, Sw_κ, Sw_{ci} and Sw_{co} are rated power in kW, rated wind speed, cut in wind speed and cut out wind speed in m/s respectively [32] [126]. The wind speeds are indicated in Fig. 3.3. As in the case of PV module, the wind mill output power for the life span of the project is determined by taking into account the energy reduction due to ageing of wind mill and replacement of wind mill.

$$\left.\begin{aligned} Pw_{t_j} &= 0 \text{ when } Sw_t < Sw_{ci} \; or \; Sw_t > Sw_{co} \\ &= Pw_{\kappa j}\frac{Sw_t - Sw_{ci}}{Sw_\kappa - Sw_{ci}} * \sum_{\tau=1}^{2}\frac{\omega_\tau}{2} * \left[2 - (\omega_\tau - 1) * \eta_w\right] \text{ when } Sw_{ci} \le Sw_t < Sw_\kappa \\ &= Pw_{\kappa j} * \sum_{\tau=1}^{2}\frac{\omega_\tau}{2} * \left[2 - (\omega_\tau - 1) * \eta_w\right] \text{ when } Sw_\kappa \le Sw_t \le Sw_{co} \end{aligned}\right\} \tag{3.7}$$

Where η_w is the efficiency reduction per year of wind mill due to ageing, τ is the turn of replacement and ω_τ is the life span of wind mill at τ^{th} replacement.

3.4.2 Commercial modelling of wind mill

C_{w_j} is the net investment of a wind mill rating j kW. This investment has five components

$$C_{w_j} = A_{1w_j} + A_{2w_j} + A_{3w_j} - A_{4w_j} + A_{5w_j} \tag{3.8}$$

Where A_{1w_j} to A_{4w_j} are components of net investment of wind mill similar to a PV module. A_{5w_j} is replacement cost of wind mill with q and h [78]. The ICC of wind mill obtained from various previous works is tabulated in Table A2 of Appendix. The ICC of 1kW wind mill in literature vary from 1065$ [8] to 3500$ [74]. The O&M cost varies from 1.5% [8] to 5% [74]. O&M cost is not considered for some works. The replacement cost is taken into account in some works which is less than ICC [72], [81].

The cost of wind mill is also reducing in market. In 2014, the market price wind mill varied from 600$ to 1100$ per kW [130], [132]. The price at consumer end is determined similar to that of PV module.

The wind mill investment cost has a fixed component and a variable component. The variable component is proportional to the rating of wind mill. It is expressed as

$$C_{w_i} = \chi_w * j + \sigma_w \tag{3.9}$$

Where χ_w and σ_w are constants and j is the rating of wind mill in kW

3.5 Inverter with MPPT Controllers

3.5.1 Technical modelling of inverter with MPPT controllers

The MPPT controllers extract maximum power from each of RES and feeds through inverter either to the load or battery according to the time of use, consumption, and battery SOC. The excess energy generated in RES after meeting load and battery charging will be fed into the grid if the grid is smart to accept the distributed RE generated through the inverter. There is power loss in inverter and MPPT controllers due to heating of electronic components. This is taken into account to determine output power of RES. This loss in inverter with MPPT controller is available in the product specification as efficiency which is expressed as η_v. This is considered in the final modelling of output power of RES as

$$Ps_{t_i} = Ps_{\kappa r}\left[1-(T_t-25)*T_{cp}\right]*\aleph_t*i*\frac{\omega}{2}*\left[2-(\omega-1)*\eta_s\right]*\eta_v \tag{3.10}$$

for solar PV system and

$$\left.\begin{aligned} Pw_{t_j} &= 0 \quad \text{when} \quad Sw_t < Sw_{ci} \ or \ Sw_t > Sw_{co} \\ &= Pw_\kappa \frac{Sw_t - Sw_{ci}}{Sw_\kappa - Sw_{ci}} * \sum_{\tau=1}^{2} \frac{\omega_\tau}{2} * \left[2-(\omega_\tau - 1)*\eta_w\right] * j \ * \eta_v \ \text{ when } \quad Sw_{ci} \le Sw_t < Sw_\kappa \\ &= Pw_\kappa * \sum_{\tau=1}^{2} \frac{\omega_\tau}{2} * \left[2-(\omega_\tau - 1)*\eta_w\right] * j * \eta_v \ \text{ when } \quad Sw_\kappa \le Sw_t \le Sw_{co} \end{aligned}\right\} \tag{3.11}$$

for wind mill.

3.5.2 Commercial modelling of inverter with MPPT controllers

C_{v_x} is net investment of inverter with MPPT controllers of rating x where

$$C_{v_x} = A_{1v_x} + A_{2v_x} + A_{3v_x} - A_{4v_x} + A_{5v_x} \tag{3.12}$$

Where A_{1v_x} to A_{5v_x} are components of net investment of inverter with MPPT controllers similar to that of wind mill. The ICC of inverter with MPPT controllers used in previous papers is tabulated in Table A3 of Appendix. 1kW inverter cost varies from 125$ [89] to 1363$ [71] in the published optimization works. The O&M cost is considered in some works which varies from 0.1 %

[104] to 10% [81]. The replacement cost of inverter is taken into account in some works which is equal or less than ICC [72], [81].

Market price of inverter with MPPT controllers is taken from the domestic market considering the frequent maintenance required for this. Present market price is varying from INR 20000 to INR 35000 for 1kW hybrid inverters with MPPT controllers [133].

The net investment cost of inverter with MPPT controllers has two components, a fixed value and another value proportional to the rating. It is determined as same as wind mill and it is expressed as

$$C_{v_x} = \chi_v * x + \sigma_v \tag{3.13}$$

Where χ_v and σ_v are constants and x is the rating of inverter with MPPT controllers.

3.6 Storage Battery

3.6.1 Technical modelling of storage battery

There are HPS installed with storage battery and without storage battery. If battery is installed, it has to be modelled considering its present SOC. An initial SOC is assigned to the storage device. The SOC at each hour is determined based on the charging or discharging of the battery in the previous hour. The state of battery i.e., whether it is charging or discharging is also determined by monitoring its present SOC and time of day. This will also vary with the HPS. These will be explained in detail in the corresponding HPS in section 4.4 and 6.4.

3.6.2 Commercial Modelling of Storage Battery

The storage device used in the proposed system is solar lead acid battery. The commercial modelling of storage device is done as

$$C_{b_k} = A_{1b_k} + A_{2b_k} + A_{3b_k} - A_{4b_k} + A_{5b_k} \tag{3.14}$$

The lead acid battery cost varies from 56$to 268$ for 1kWh in the published works as tabulated in Table A4 of Appendix. In the case of storage battery also the replacement cost is less than or equal to ICC. The domestic market price is taken into account in the storage device by considering its periodic replacement. The present market price varies from INR 8000 to INR12000 for 1kWh [133].

In the calculation of life time O&M cost and insurance charges g and h are taken into account. Salvage value at the end of the project and replacement cost are found out with h and q [78]. CRF is applied to all cost since the return of investment is monthly. C_{b_k} is proportional to the rating of battery. So it can be expressed as

$$C_{b_k} = \chi_b * k \tag{3.15}$$

3.7 Method to Determine each Component of Commercial Model

The commercial modelling of different components of HPS is explained in sections 3.3, 3.4, 3.5 and 3.6. The commercial models have different components. The estimations of different components are given in this section.

3.7.1 Capital investment

Capital investment with CRF for the life span of the component $\left(A_1\right)$ is determined.

$$A_1 = A_{11} * F(\alpha, \beta) * \beta \tag{3.16}$$

$$F(\alpha, \beta) = \frac{\alpha * (1+\alpha)^{\beta}}{(1+\alpha)^{\beta} - 1} \tag{3.17}$$

Where A_{11} is the initial capital investment, α is rate of interest and β is span of investment [102], [103], [120].

3.7.2 O&M cost

The O&M cost (A_2) is determined [78] as

$$A_2 = A_{22} * \sum_{y=1}^{\omega} \left(\frac{1+g}{1+h} \right)^{y} * F(\alpha, \beta) * \beta \tag{3.18}$$

Where A_{22} is the present O&M cost and y is the turn of project year.

3.7.2 Insurance charge

The method for O&M cost is also followed for life time insurance charge (A_3) calculation. It is determined as

$$A_3 = A_{33} * \sum_{y=1}^{\omega} \left(\frac{1+g}{1+h} \right)^{y} * F(\alpha, \beta) * \beta \tag{3.19}$$

Where A_{33} is the present insurance charge.

3.7.3 Salvage value

The salvage value is found out from present salvage value (A_{44}) [78] as

$$A_4 = A_{44} * \frac{(1+q)^{\beta}}{(1+h)^{\beta}} \tag{3.20}$$

3.7.4 Replacement cost

Replacement cost$\left(A_5\right)$is determined considering CRF and general inflation rate with interest rate evolution [103], [130].

$$A_5=\sum_{\tau=1}^{c} A_{11} * \frac{\left(1+q\right)^{\tau*\beta}}{\left(1+h\right)^{\tau*\beta}} * F\left(\alpha,\beta\right) * \beta \tag{3.21}$$

Where τ is the turn of replacement and c is the number of replacement in the project life time.

3.8 Cost of Energy from Utilities

It is possible that instead of having HPS, energy can be purchased from utilities. For cost analysis, it is necessary to model the energy cost drawn from utilities. The cost of energy depends on energy consumed at specific intervals in a day. For the purpose of the analysis the period are classified into three namely peak, normal and off peak. An hourly load profile for a typical day is shown in Fig. 3.4 with specific peak, normal and off peak period [134]. The energy costs during these periods are respectivelyr_m ,$r_n$and r_o for each kWh. In addition, another cost components are for each kW of the connected load of the premises and monthly fixed charge per kW. These are respectively taken asψ andξ . Hence the utility energy cost for the life span of project is estimated as

$$C_{\Theta}=\left[\sum_{d=1}^{365}\sum_{t=t_1}^{t_2} Pl_{dt} * r_m + \sum_{d=1}^{365}\sum_{t=t_2}^{t_3} Pl_{dt} * r_o + \sum_{d=1}^{365}\sum_{t=t_3}^{t_1} Pl_{dt} * r_n + \psi * \xi * 12\right] * \omega \tag{3.22}$$

Where Pl_{dt} is the load of the premises at time t and day$d$. The tariff structure of Kerala, India in 2013 and 2014 are tabulated in Table A5 of Appendix [134]. The commercial energy charge in Kerala has gone upto INR.9.30/unit with fixed charge INR130/kW for the financial year 2014-15. The cost of conventional energy cost and grid energy cost for the buildings with HPS are determined in view of the tariff structure of Kerala. Yearly enhancement of tariff is also taken into account to determine life time conventional energy of the premises.

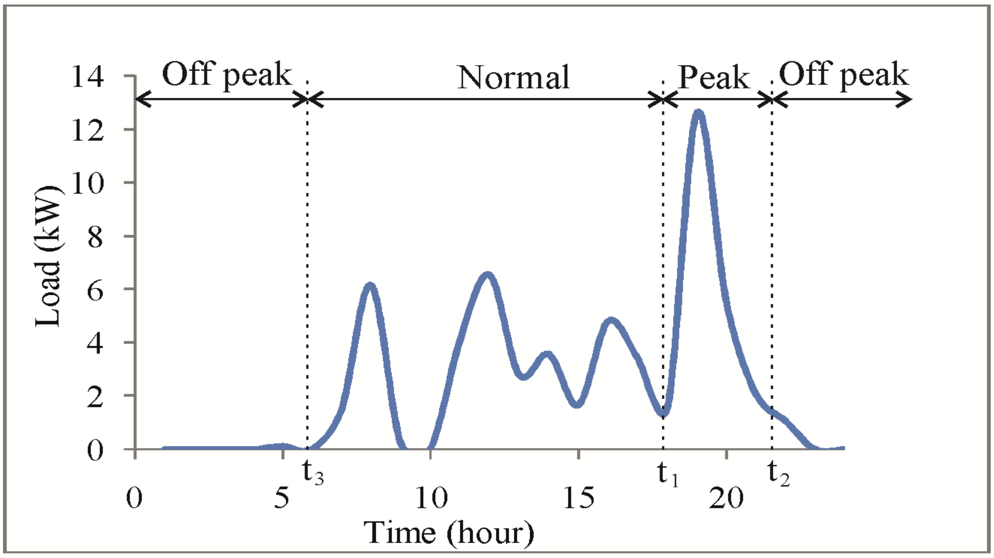


Fig. 3.4 Hourly load profile of a typical day of load1

3.9 Methodology

Models of HPS for distributed RE generation are designed to determine optimal system for any desired location and load for different conditions of grid and HPS. MATLAB coding is used for the development of HPS model and optimization algorithm.

HPS is proposed to be installed at the roof top of the building. The block diagram of the typical proposed system is shown in Fig. 3.1. HPS consists of PV module and wind mill as RES and lead acid tubular battery as storage device. The inverter with MPPT controller is the interlinking device for RES, storage device and grid. Models for each part of HPS are developed. Algorithm is developed to optimize the sizing of RES by satisfying the objective function and constraints. The inputs to the system are hourly solar irradiance, temperature of the cell and wind speed in the desired location. The hourly load profile of the desired premises is also fed into the system model. The model is developed for one year using the corresponding input data.

Three standard configurations of HPS namely conventional grid tied, smart grid tied and smart grid tied with storage device are designed to determine energy cost for the life time of RES. The excess energy generated in the premises will be stored in battery if the proposed configuration has storage device. The stored energy in the battery is used in peak hours if needed. This will reduce the consumption at peak hours from grid to make the grid energy generation uniform throughout the day. Capital investment to meet peak demand can be reduced for the utility if the storage devices were properly maintained. Green energy credit (GEC) had been taken into account in the problem formulation in view of promoting green energy which is explained in section 4.3.4. Peak energy credit (PEC) may also be implemented by the utility for peak energy consumption reduction and peak hour energy supplied to the grid considering the reduction in capital investment of utility to meet the peak demand which is explained in section 4.3.9. RE generation and CO_2 emission reduction are also determined for optimal system to analyse the environmental impact. RE generation and CO_2 emission reduction are explained in section 4.3.2 and 4.3.3 respectively. Every cost in this work is in INR.

3.10 Conclusion

A typical system consisting of PV module, wind mill, inverter with MPPT controllers and storage battery is considered for analysis. The technical and commercial modelling of each component is formulated in this chapter. Also the cost of energy had it been drawn from conventional system for a typical load curve is also derived. These models will be used for optimal operation of the HPS in chapters 4, 5 and 6.

Chapter 4

Conventional Grid Tied Hybrid Power System

4.1 Introduction

The increase in demand of electricity and depletion of fossil fuel lead the authorities to promote distributed RE generation which contributed reduction in CO_2 emission. In many countries the grid is not capable to accept energy from distributed RE generation due to the shortage of grid capacity and the absence of advanced equipments for energy security and protection [127]. So only way to promote distributed RE generation is by using HPS connected to single directional grid. The HPS consists of PV module, wind mill and storage battery. The battery acts as storage device for excess energy generation and if it is fully charged the excess energy generated is considered as dump load. In this chapter HPS with single directional grid is modelled to determine optimal combination for least energy cost satisfying the constraints in a desired site condition and demand. The grid connected to the premises can deliver energy when there is shortage in generation from HPS. Constraints like minimum average SOC of the battery bank, maximum dump load, minimum RE generation with respect to renewable energy obligation (REO) etc are also taken into account for the optimization. The optimal HPS is determined for minimum energy cost for the life span of the project. The analysis is also carried out considering with only one of the RES in the system. The GEC and PEC are considered in cost analysis. The determination of demand of the premises, peak reduction in energy, RE generation and CO_2 emission reduction is also part of algorithm. Coding used for these are developed by the author.

4.2 Description of the Conventional Grid Tied Hybrid Power System Configuration

The HPS includes PV module and wind mill as RES with lead acid tubular battery as storage device. These are interconnected through conventional grid tied inverter with MPPT controller. MPPT for each RES are also included in the system configuration. Each MPPT extracts maximum possible power from RES for a given solar irradiance or wind speed.

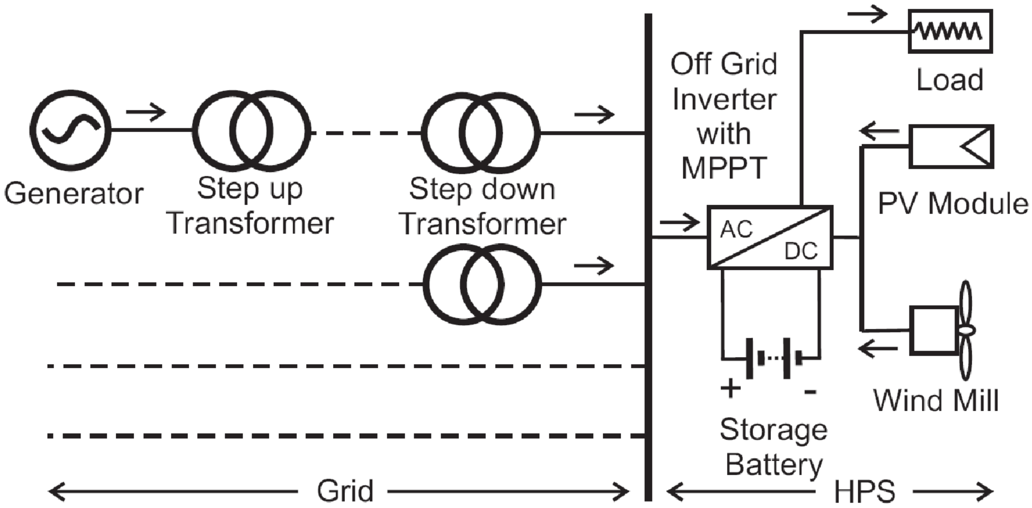


Fig. 4.1 One line diagram of conventional grid tied HPS with power flow of grid

The one line diagram with power flow of grid is shown in Fig. 4.1 and the proposed HPS configuration is shown in Fig. 4.2.

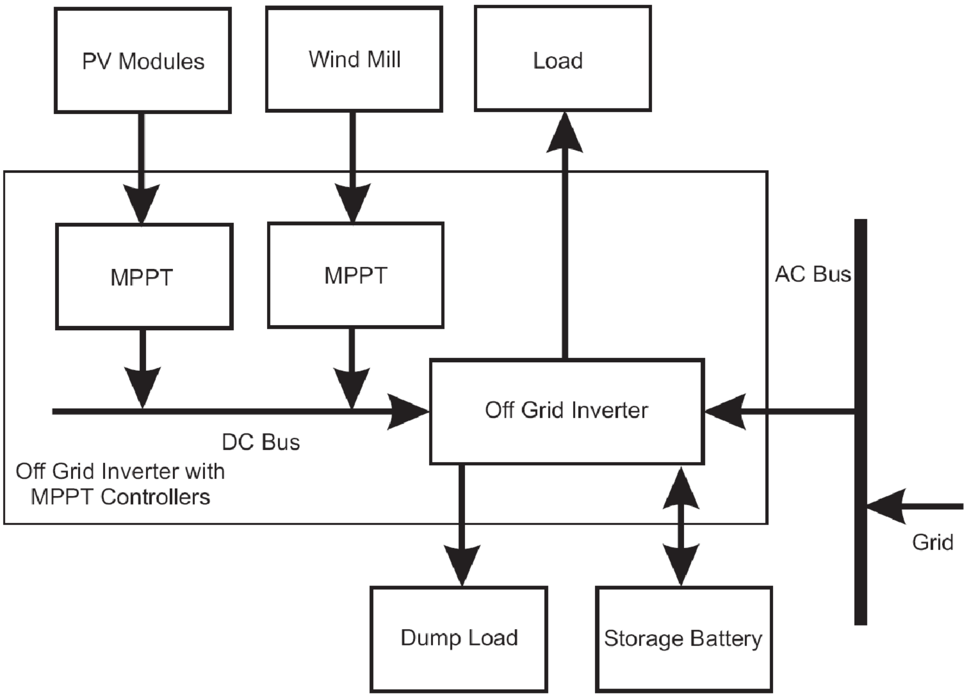


Fig. 4.2 Configuration of the conventional grid tied hybrid power system

The energy generated by RES is utilised to charge the battery during intervals when energy generation is greater than demand. Under this condition the battery is fully charged the excess energy available is considered as dump load. The minimum SOC of battery is fixed in different values for peak and other times of the day to utilise maximum stored energy at peak hours, obtain desired average SOC to enhance the life span of battery and reduce dump load. The priority of energy utilisation by the load is RES, battery and grid in the order of availability.

4.3 Mathematical Formulation

4.3.1 Utility energy cost of conventional grid tied premises

The shortage of energy in the premises is met from the grid in the proposed system. The cost of energy drawn from grid is determined from hourly shortage of energy in the premises in the life span of the project. The energy cost is determined considering the time slot as peak, off peak and normal hours in the time of the day. The fixed charge imposed by the utility for the connected load of the premises is also taken into account in the energy cost modelling. It is expressed as

$$C_{\pi_{ij}} = C_{\pi m_{ij}} + C_{\pi o_{ij}} + C_{\pi n_{ij}} + C_{\zeta} \tag{4.1}$$

That is determined as

$$C_{\pi m_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_1}^{t_2} \left[+ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * r_m \right] * \omega \tag{4.2}$$

$$C_{\pi o_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_2}^{t_3} \left[+ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * r_o \right] * \omega \tag{4.3}$$

$$C_{\pi n_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_3}^{t_1} \left[+ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) - \phi dc_{dt_{ij}} \right] * r_n \right] * \omega \tag{4.4}$$

$$C_{\zeta} = \psi * \xi * 12 * \omega \tag{4.5}$$

Where $\phi dc_{dt_{ij}}$ is the battery discharge at time *t* and day *d*. $C_{\pi m_{ij}}$, $C_{\pi o_{ij}}$ and $C_{\pi n_{ij}}$ are the peak, off peak and normal energy cost respectively for the energy drawn from grid for the life span of project for *i* rating PV module and *j* rating of wind mill. C_{ς} is the fixed charge for the life span of the project.

4.3.2 Objective function of conventional grid tied hybrid power system

The objective function to determine optimal HPS satisfying constraints is developed to minimize the energy cost of the premises. The objective function is

Minimize:

$$C_{\varphi_{ij}} = C_{s_i} + C_{w_j} + C_{v\square_x} + C_{b_k} + C_{\pi_{ij}} - C_{\mu\square_{ij}} \tag{4.6}$$

It is net energy cost of the premises for the life span of the project. Where $C_{v\square_x}$ and $C_{\mu\square_{ij}}$ are the net investment cost of conventional grid tied inverter of *x* rating and GEC for conventional grid tied system for *i* rating of PV module and *j* rating of wind mill respectively.

4.3.3 Constraints applied for conventional grid tied hybrid power system

REO is implemented by the governments to promote generation of RE [135], [136]. The authority insisted the consumers to purchase a certain percentage consumption from RES or to generate certain quantity of RE in their premises itself to satisfy REO. In this work the RE is generated in the premises itself. So the consumer has to generate RE to a certain percentage (*u*) of consumption of the premises to satisfy REO which is expressed as

$$Eg_{ij} \geq \frac{El * u}{100} \tag{4.7}$$

Where Eg_{ij} is the RE generated in for the life span of the project for i rating of PV module and j rating wind mill and El is the consumption of the premises in a year

Another constraints applied in the model are dump load and average SOC of battery. Dump load reduction is termed as

$$E_{dump_{ij}} < \wp * Eg_{ij} \tag{4.8}$$

Where $E_{dump_{ij}}$ is the dump load for one year for PV module rating i and wind mill rating j and $\wp$ is the factor of dump load reduction with respect to RE generated.

Maximum and minimum SOC of the storage battery should be maintained within the limit to avoid depletion and overcharging. In this work minimum SOC is fixed at two values in peak and other times of the day to utilize maximum battery capacity at peak hours. Then the system should be satisfied at peak hours

$$SOC_{\min 1} \leq SOC_{dt_{ij}} \leq SOC_{\max} \tag{4.9}$$

At other times of the day

$$SOC_{\min 2} \leq SOC_{dt_{ij}} \leq SOC_{\max} \tag{4.10}$$

The average SOC of the battery ($SOC_{a_{ij}}$) should be greater than a desired value (λ) to ensure the life span of the battery.

$$SOC_{a_{ij}} > \lambda \tag{4.11}$$

To determine the rating of the storage battery (k_{ij}) for PV module rating i and wind mill rating j in the iteration

$$k_{ij} = Round\left(\sum_{d=1}^{365} \sum_{t=1}^{24} \frac{+ve(Ps_{dt_i} + Pw_{dt_j} - Pl_{dt})}{300} \right) \tag{4.12}$$

The constraints to ensure the maximum and minimum rating of PV module and wind mill are not violated.

$$i_{\min} \leq i \leq i_{\max} \tag{4.13}$$

$$j_{\min} \leq j \leq j_{\max} \tag{4.14}$$

The modelling of the HPS is done to analyse the objective function with these constraints and then optimal HPS is found out.

4.3.4 Green energy credit

The government is offering subsidy for the RES on the initial capital investment at the starting of the project. This may reduce the life span utilization of the installed capacity of RES due to minor damages or reluctance in maintenance. The GEC for each unit of green energy generation may overcome this issue. The GEC offered by the government should be calculated depending upon the availability of RES and to make the rate attractive to the customer. Also the financial burden to the government should be justifiable considering the GHG emission reduction and capital investment for the excess conventional generation to meet the peak demand. In this work the subsidy provided by the government is converted to monthly payment for the life span of the project as GEC. GEC for the life span of project is determined as

$$C_{\mu_{ij}} = \left(A_{11s_i} + A_{11w_j} + A_{11v_x} + A_{11b_k} \right) * F\left(\alpha, \omega\right) * \omega * \varepsilon \tag{4.15}$$

ε is the percentage of subsidy provided on the initial capital investment. A_{11s_i}, A_{11w_i}, A_{11v_x} and A_{11b_k} are the initial capital investment for PV modules of i rating, wind mill of j rating, inverter with MPPT controller of rating x and battery of k rating respectively . These are determined as

$$A_{11s_i} = \delta_s * i \tag{4.16}$$

$$A_{11w_j} = \delta_w * j + \lambda_w \tag{4.17}$$

$$A_{11v_x} = \delta_v * x + \lambda_v \tag{4.18}$$

$$A_{11b_k} = \delta_b * k \tag{4.19}$$

δ_s, δ_s, δ_s, δ_s, λ_w and λ_w are the constants determined from the initial investment calculation for various ratings of each component of HPS.

4.3.5 Renewable energy generation

RE generated in the premises $\left(Eg_{ij}\right)$ for the life span of project can determined by summing up the energy generated both by PV module and wind mill.

$$Eg_{ij} = \left[\sum_{t=1}^{8760} Ps_{t_i} + Pw_{t_j}\right] * \omega \tag{4.20}$$

This is an indicator of the environmental impact of the proposed HPS. CO_2 emission reduction is proportional to RE generated.

4.3.6 Demand of the premises

Demand of the premises $\left(El\right)$ for the life span of the project is found out as

$$El = \left[\sum_{d=1}^{365} \sum_{t=1}^{24} Pl_{dt} \right] * \omega \tag{4.21}$$

This is the requirement of electrical energy of the premises in a year. This can be compared with the RE generated by an optimal system to know about the contribution of HPS in the premises.

4.3.7 CO₂ emission reduction

CO_2 release rate from a coal combustion power plant would be 0.95242 $kgCO_2/kWh$. CO_2 emission rate for complete combustion of crude oil is computed as 0.71046 $kgCO_2/kWh$ where as for natural gas it is 0.46636 $kgCO_2/kWh$ [137]. The average CO_2 emission rate is taken to calculate CO_2 emission reduction $\left(\Delta_{ij}\right)$ due to RE generation.

$$\Delta_{ij} = 0.7097 * Eg_{ij} \tag{4.22}$$

4.3.8 Peak reduction in energy

There is a reduction in peak demand ($E_{\varsigma m_{ij}}$) for i rating of PV module and j rating of wind mill in conventional grid tied premises due to RE generation and battery storage. This is determined as

$$E_{\varsigma m_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_1}^{t_2} Pl_{dt} - \sum_{d=1}^{365} \sum_{t=t_1}^{t_2} {+ve}(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) + \phi dc_{dt_{ij}} \right] * \omega \tag{4.23}$$

The percentage reduction of peak demand with respect to the demand of the premises is also determined to analyse the benefit of conventional grid tied HPS.

$$E_{\varsigma m\%_{ij}} = \frac{E_{\varsigma m_{ij}} * 100}{\sum_{d=1}^{365} \sum_{t=t_1}^{t_2} Pl_{dt} * \omega} \tag{4.24}$$

4.3.9 Peak energy credit

The reduction of peak load is very beneficial for both grid and utility. The grid become stable and utility can reduce the investment for conventional generators to meet the peak load. The generators efficiency can also be improved due to peak load shaving. This benefit may be contributed to producers of RE with respect to peak demand reduction. This is termed as PEC. The effect of PEC is also analysed in this paper. The PEC for i rating PV module and j rating of wind mill is

$$C_{\rho_{ij}} = E_{\varsigma m_{ij}} * \hbar \tag{4.25}$$

Where $\hbar$ is per unit PEC with respect to peak energy generation.

4.4 Simulation

The HPS connected to single directional grid is modelled both technically and commercially to determine optimal HPS for a desired location and load. The optimal system should satisfy constraints as discussed above. The values of constants used for the simulation are shown in Table 4.1.

The flow chart for optimization program is shown in Figs. 4.3 and 4.4. The RES are modelled to get hourly output power. The maximum rating of PV module and wind mill is determined in such a way that individually each one can deliver the yearly consumption of the premises. The roof top capacity of the premises is also a limiting factor for the maximum rating of RES.

That is the maximum rating of the PV module and wind mill is limited by excess energy generated in the premises in a year is less than or equal to zero for any combination of HPS or the rating of RES which can install on the roof top which one is low. The excess energy generated in the premises in a year for i rating of PV module and j rating of wind mill is described as

$$E_{ij} = \sum_{d=1}^{365} \sum_{t=1}^{24} Pl_{dt} - Ps_{dt_i} - Pw_{dt_j} \tag{4.26}$$

The technical modelling of storage battery is done by determining its SOC in each hour. Hourly SOC of the battery is determined considering SOC of the battery in the last hour and excess energy generated by the HPS in present hour. The methods for determining hourly SOC, charge and discharge of the battery are detailed in Fig. 4.4.

There is loss in batteries at charging and discharging. This is taken into account in battery modelling as charging efficiency (η_b). The hourly excess energy generated for i rating PV module and j rating of wind mill is determined as

$$P_{dt_{ij}} = Ps_{dt_i} + Pw_{dt_j} - Pl_{dt} \tag{4.27}$$

If $P_{dt_{ij}}$ is less than zero, there is no excess generation in the premises. Then -$P_{dt_{ij}}$ is the shortage of energy in the premises. If SOC of the battery is higher than SOC_{min} the shortage of energy is met from the battery.

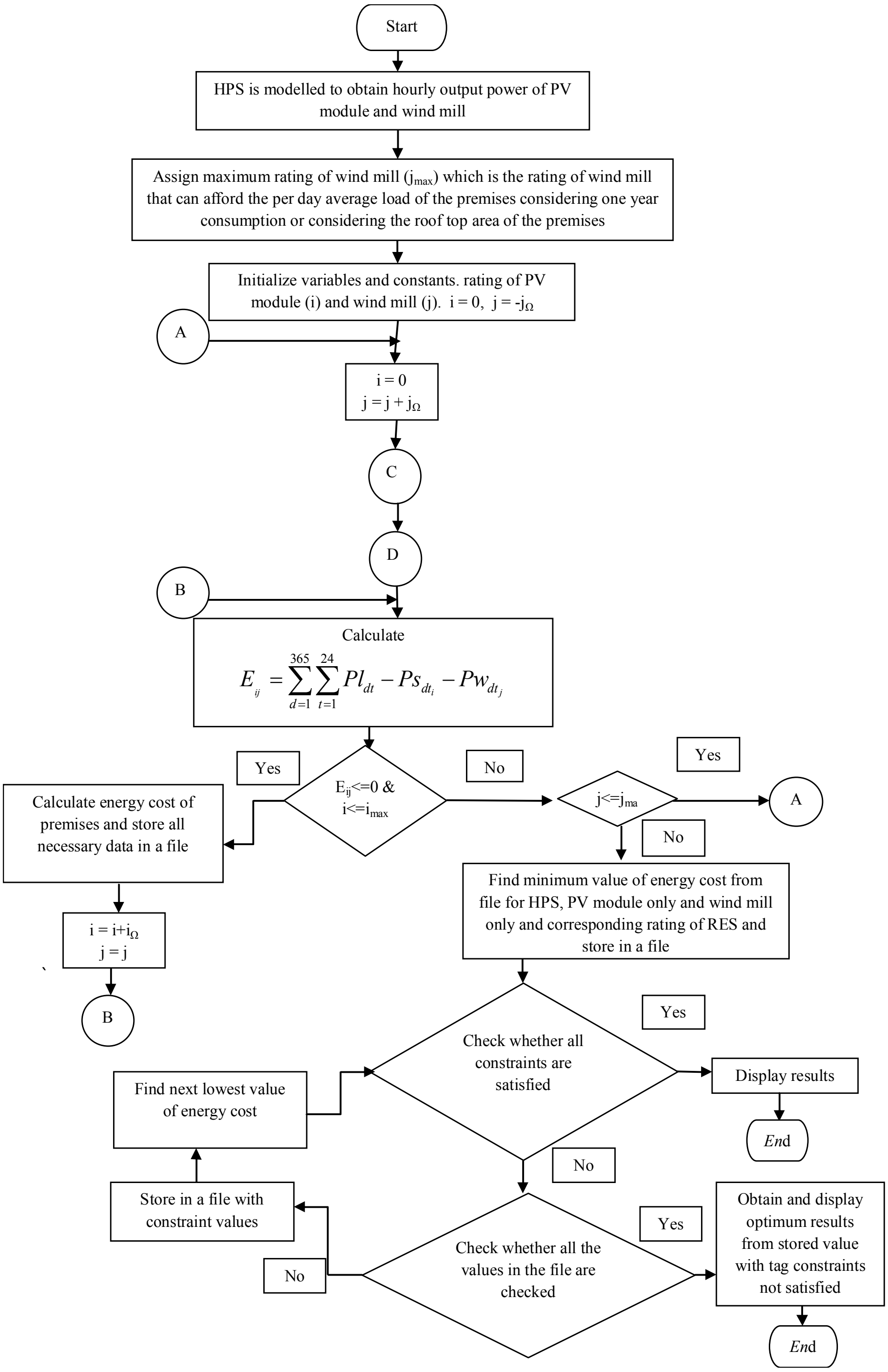


Fig. 4.3 Optimization flow chart of conventional grid tied System

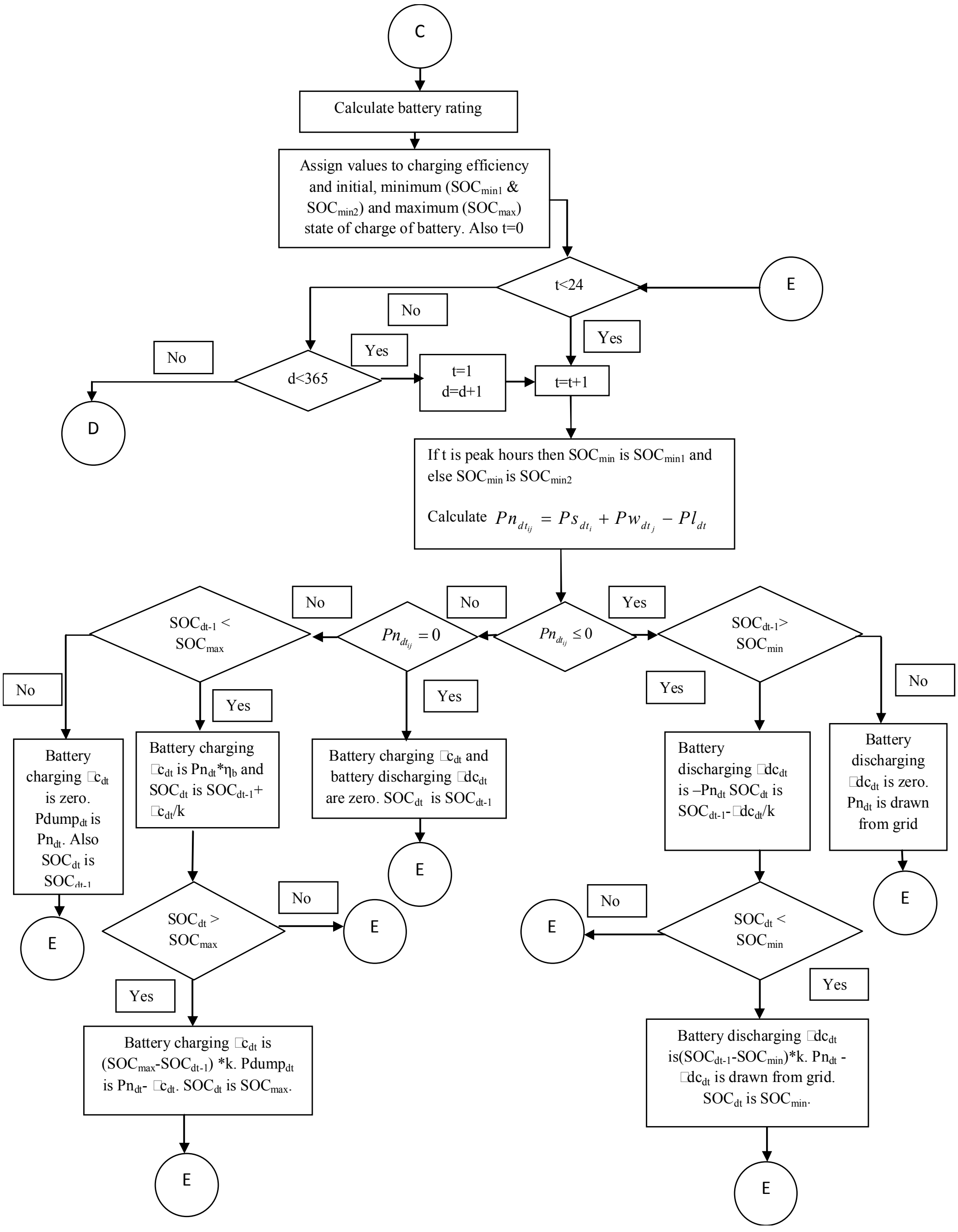


Fig. 4.4 Battery state of charge algorithm of conventional grid tied system

Table 4.1 Simulation parameters and respective values

Sl. No.	Parameters	Unit	Values
1	T_{cp}	%/^{o}C	0.4
2	Sw_{κ}	m/s	11
3	Sw_{ci}	m/s	3
4	Sw_{co}	m/s	35
5	g	%	10
6	h	%	7
7	q	%	8
8	ε	%	30
9	ω	years	25
10	r_m	INR	17
11	r_n	INR	13
12	r_o	INR	10
13	$r_{\partial m}$	INR	5.78
14	$r_{\partial n}$	INR	5.78
15	$r_{\partial o}$	INR	5.78
16	t_1	hr	18
17	t_2	hr	22
18	t_3	hr	06
19	ψ	INR	300
20	η_b	%	80
21	Λ	%	50
22	α	%	7
23	*β for PV module*	years	25
24	*β for wind mill*	years	15, 10
25	*β for inverter with controller*	years	12.5
26	*β for storage battery*	years	5
27	*β for O&M*	years	1
28	*β for insurance*	years	1

The battery discharge is ϕdc_{dt} and SOC_{dt} is $SOC_{dt-1} - \phi dc_{dt} /k$. If SOC_{dt} is less than SOC_{min} the battery can discharge only $(SOC_{dt-1}-SOC_{min})*k$. $P_{dt_{ij}} - \phi dc_{dt}$ is drawn from grid and SOC_{dt} is SOC_{min}. If SOC_{dt-1} is less than or equal to SOC_{min}, ϕdc_{dt} is zero and $P_{dt_{ij}}$ is drawn from grid [11], [71], [78].

If Pn_{dt} is greater than zero, the excess energy produced in the premises is utilised to charge battery if the battery in not fully charged. Battery charging energy ϕc_{dt} is $Pn_{dt}*\eta_b$ and the SOC_{dt} is $SOC_{dt-1}+ \phi c_{dt}/k$. If SOC_{dt} is greater than SOC_{max}, the battery charging energy ϕc_{dt} is $(SOC_{max}-SOC_{dt-1})*k$. The dump load $Pdump_{dt}$ is $Pn_{dt}- \phi c_{dt}$ and SOC_{dt} is SOC_{max}. If SOC_{dt-1} is equal to SOC_{max}, the dump load $Pdump_{dt}$ is Pn_{dt} and ϕc_{dt} is zero. If Pn_{dt} is equal to zero, ϕdc_{dt} and ϕc_{dt} are zero and SOC_{dt} is SOC_{dt-1}. In this way each hour SOC is determined with dump load and peak energy contribution from storage battery [11], [71], [78].

The objective function is formulated to obtain energy cost of premises for various combinations of HPS with PV module rating with i_u kW increment and wind mill rating of j_u kW increment. These are determined to find out optimal HPS with minimum energy cost satisfying the constraints. The RE generation, CO_2 emission reduction, dump load, average SOC of the storage battery and peak demand reduction are also determined in this simulation. The initial condition for rating of PV module is 50W, rating of wind mill is 1kW, rating of inverter with MPPT controller is 1kW and SOC of storage battery is 0.5. Linear optimization algorithm is developed in MATLAB by specific coding.

4.5 Analysis

Several locations in southern region of India are selected for analysis. The variation in solar irradiance and temperature in selected locations does not make considerable change in the ratings of optimal system for a desired demand profile. The wind availability is high at many locations at Tamilnadu compared to Kerala. The optimal system for a desired demand profile is different for different locations according to the wind availability. Finally two high wind locations and one low wind location are selected for analysis.

Table 4.2 Energy demand of premises

Particulars	Unit	Load1	Load2
Project life span energy demand of the premises	kWh	589810.24	196603.40
Project life span conventional energy cost	INR in lakh	108.73376	36.54125

The model is applied at location1 (Theni) and location2 (Kayathar) both in Tamilnadu, India which are high wind locations and location3 (Thrissur) in Kerala, India which is low wind location. Two types of demand profiles are selected according to change in demand of the premises. The details of loads as detailed in Table 4.2 are considered at all three locations. The initial capital investments considered for this work for each component of HPS are tabulated in Table 6A of Appendix.

The solar irradiance and wind speed data are available from National Renewable Energy Laboratory, USA and National Institute of Wind Energy, India [70], [137]. The temperature of PV cell is determined from the temperature data from climate data site [138]. The hourly demand of the premises is obtained from Time of day (TOD) meter installed in the premises. These hourly data for one year for three locations and two demand profiles are taken for analysis to incorporate seasonal changes both in site conditions and demand profile. Hourly data for one day for three locations are shown in tables 7A, 8A and 9A of Appendix.

Table 4.3 Optimal rating of HPS and individual RES of conventional grid tied system

Particulars	**Unit**	**Load1**			**Load2**		
		HPS	**PV only**	**W only**	**HPS**	**PV only**	**W only**
Location1	kW	PV-2.35 *W-3.00 **B-16.00 ***IC-5.00	PV-6.45 B-16.00 IC-6.00	W-5.00 B-22.00 IC-5.00	PV-1.10 W-1.00 B-6.00 IC-2.00	PV-2.15 B-5.00 IC-2.00	W-2.00 B-9.00 IC-2.00
Location2	kW	PV-2.30 W-3.00 B-15.00 IC-5.00	PV-6.45 B-16.00 IC-6.00	W-5.00 B-20.00 IC-5.00	PV-1.20 W-1.00 B-6.00 IC-2.00	PV-2.15 B-5.00 IC-2.00	W-2.00 B-9.00 IC-2.00
Location3	kW	PV-6.50 W-1.00 B-16.00 IC-8.00	PV-6.80 B-16.00 IC-7.00	W-9.00 B-3.00 IC-9.00	PV-2.10 W-1.00 B-5.00 IC-3.00	PV-2.25 B-5.00 IC-2.00	W-9.00 B-5.00 IC-9.00

*W=Wind mill **B=Battery***IC= Conventional grid tied inverter with MPPT controllers

The optimal combination of components of HPS and if only one of RES are considered for energy production the respective ratings are determined for both loads in all three locations and the results are displayed in Table 4.3. The REO, RE generation, CO_2 emission reduction, dump load, average SOC and peak demand reduction for all configurations are found out. The optimal energy cost and optimal energy cost with PEC of all configurations are determined to compare it with conventional energy cost of the premises. These are explained in the next section.

4.6 Results and Discussion

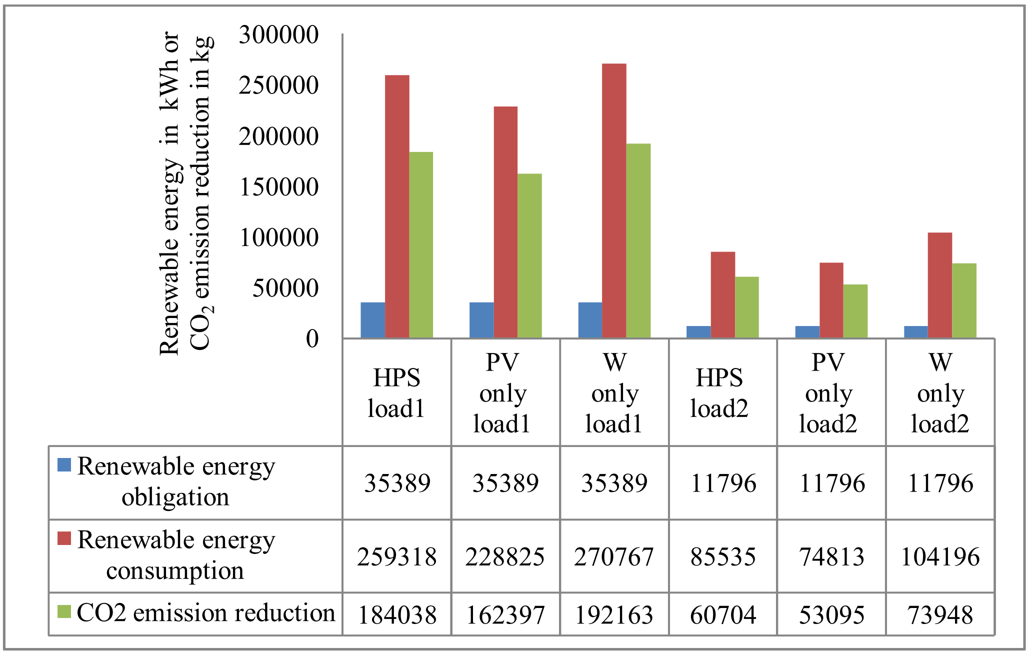
To obtain the optimal configuration of RES either single RES or a combination of RES, the following factors have to be considered.

1. RE generation and CO_2 emission reduction
2. Energy in dump load
3. Average SOC of storage battery
4. Reduction in peak demand

Optimal system configuration and optimal energy cost are determined with PV only, Wind mill only and PV and wind mill together as RES. Out of these three which gives least energy cost is found out in all three locations for the typical load curves. RE generation and CO_2 emission reduction are the factors to analyse the environmental impact of the system implementation. The wastage of energy from RES by providing conventional grid tied system is analysed by determining dump load. The life span of the storage battery depends on its average SOC. Peak demand reduction of each case is also determined to evaluate the effect of optimal conventional grid tied system in the peak load shaving. The optimal energy costs of three configurations are compared in three locations for both loads to determine most appropriate system in each case.

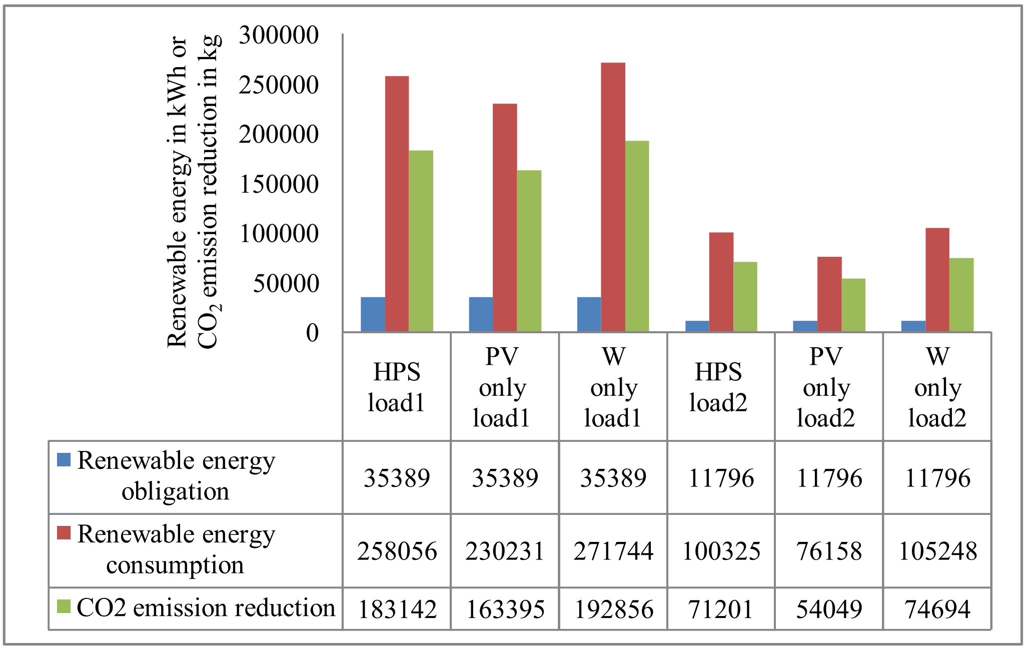
4.6.1 Renewable energy generation and CO_2 emission reduction

The RE generated in the premises cannot be fully utilised in conventional grid tied system when generation is higher than demand. A part of RE generated has been unutilised in this system. So the RE consumption of premises is taken into account for the comparison. The REO of the premises depends on the consumption of the premises. The project life time values are taken into account in this work. The RE consumption of the premises both combined and individual RES optimal system is much higher than the REO of the premises for both loads in all three locations as shown in Fig. 4.5, 4.6 and 4.7.



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy consumption	259318	228825	270767	85535	74813	104196
🟩 CO2 emission reduction	184038	162397	192163	60704	53095	73948

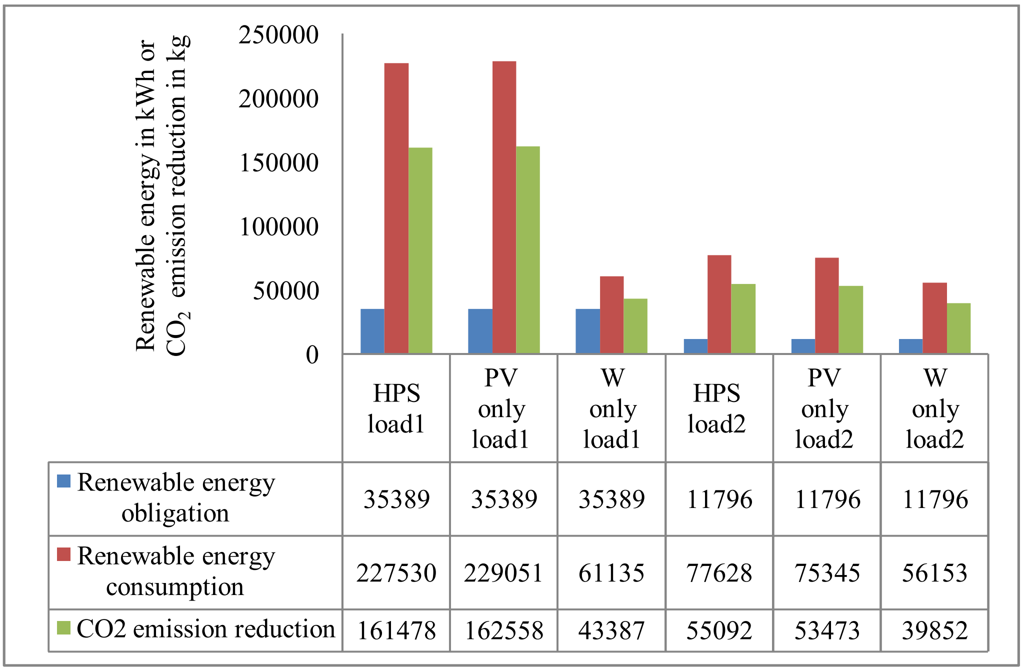
Fig. 4.5 Renewable energy obligation, renewable energy consumption and CO_2 emission reduction for both loads at location1



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy consumption	258056	230231	271744	100325	76158	105248
🟩 CO2 emission reduction	183142	163395	192856	71201	54049	74694

Fig. 4.6 Renewable energy obligation, renewable energy consumption and CO_2 emission reduction for both loads at location2

CO_2 emission reduction due to RE consumption is determined to know about environmental impact of the system. The CO_2 emission reduction for each case is plotted in the graphs. The percentage of RE consumption with respect to the total energy consumption of the premises in three locations for combined and individual RES optimal systems for load1 and load2 are displayed in Fig. 4.8 and 4.9 respectively. The RE consumption and CO_2 emission reduction are high for wind mill only condition and HPS for both loads at location1 and location2. At location3, optimal HPS and PV only condition have higher RE consumption and CO_2 emission reduction for both loads.



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy consumption	227530	229051	61135	77628	75345	56153
🟩 CO2 emission reduction	161478	162558	43387	55092	53473	39852

Fig. 4.7 Renewable energy obligation, renewable energy consumption and CO_2 emission reduction for both loads at location3

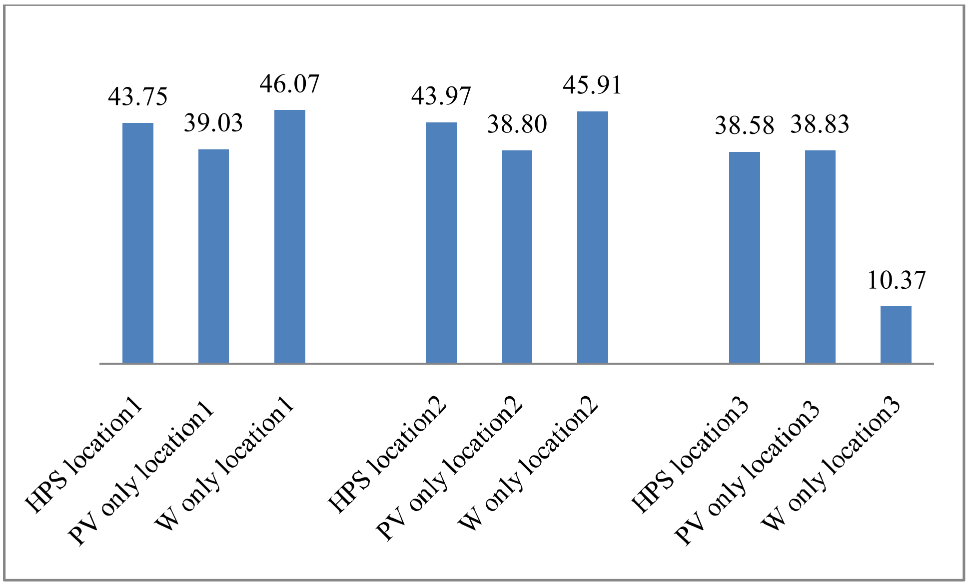


Fig. 4.8 Percentage renewable energy consumption at three locations for load1

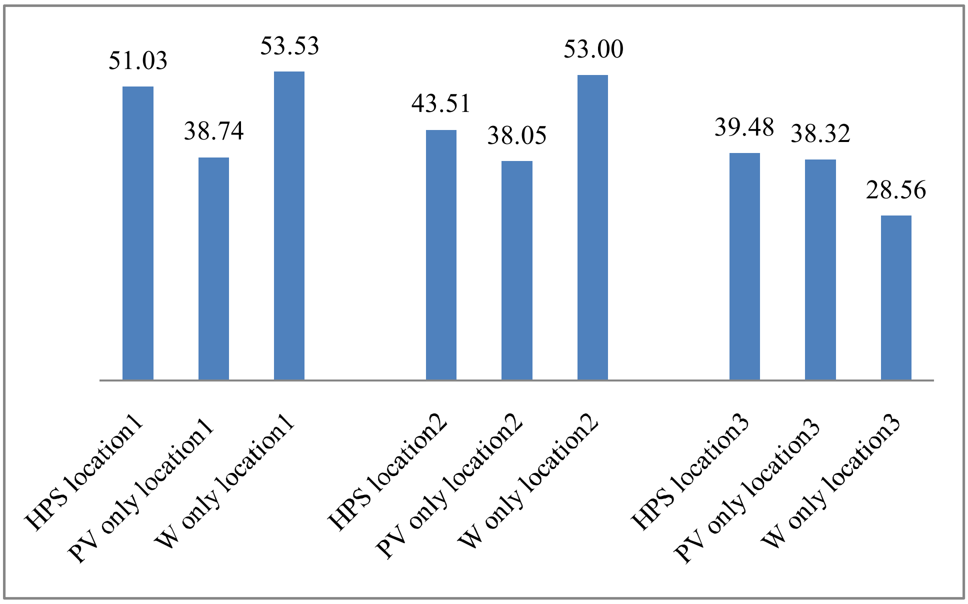


Fig. 4.9 Percentage renewable energy consumption at three locations for load2

4.6.2 Dump load

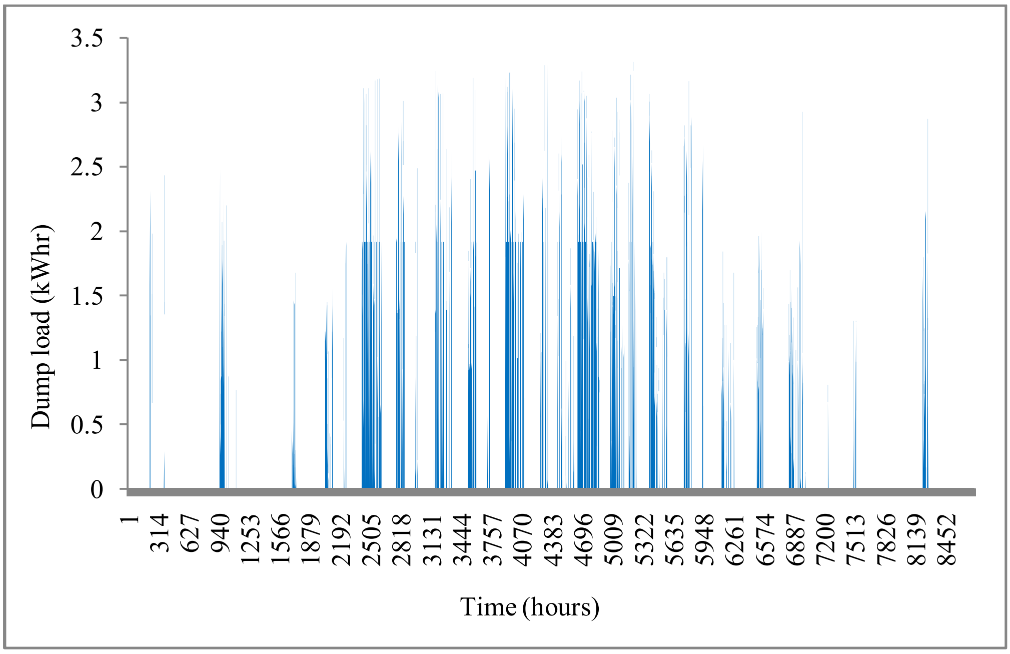


Fig. 4.10 One year hourly dump load at location1 for load1

The excess energy in the RES cannot be fed to grid in conventional grid tied system. The RE generation can be larger than the demand at certain period of time. Sometimes battery may be fully charged so that excess generation cannot be stored in the battery. Under this conditions the RE generate is fed into the dump load. The one year hourly dump load at location1 for load1 is shown in Fig. 4.10. The percentage dump load are analysed in this work. Fig. 4.11 and Fig. 4.12 show percentage dump loads with respect to RE generated in three locations respectively for combined and individual RES optimal systems for load1 and load2.

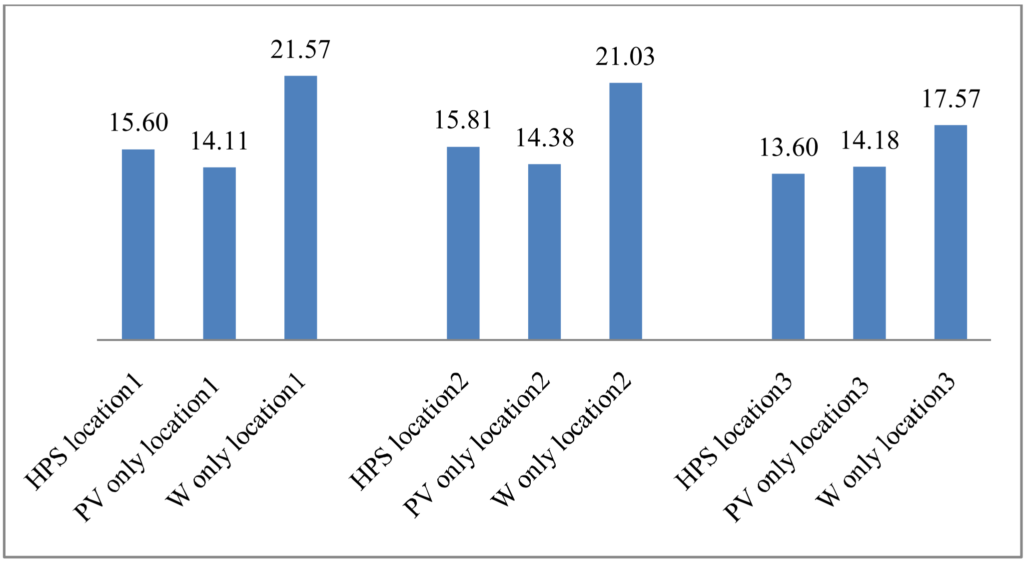


Fig. 4.11 Percentage dump load of the premises at three locations for load1

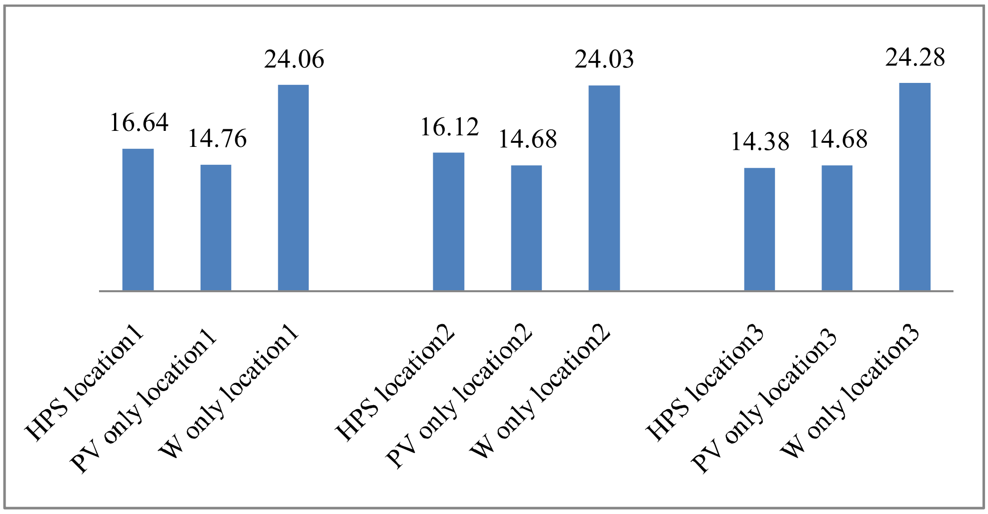


Fig. 4.12 Percentage dump load of the premises at three locations for load2

The results show that the dump load is less than 25% for all optimal systems. Wind mill only optimal system has high dump load as shown in Figs. 4.11 and 4.12 compared to HPS and PV only optimal system in three locations for both loads. So HPS or PV only systems are more preferable in terms of dump load reduction.

4.6.3 State of charge of battery

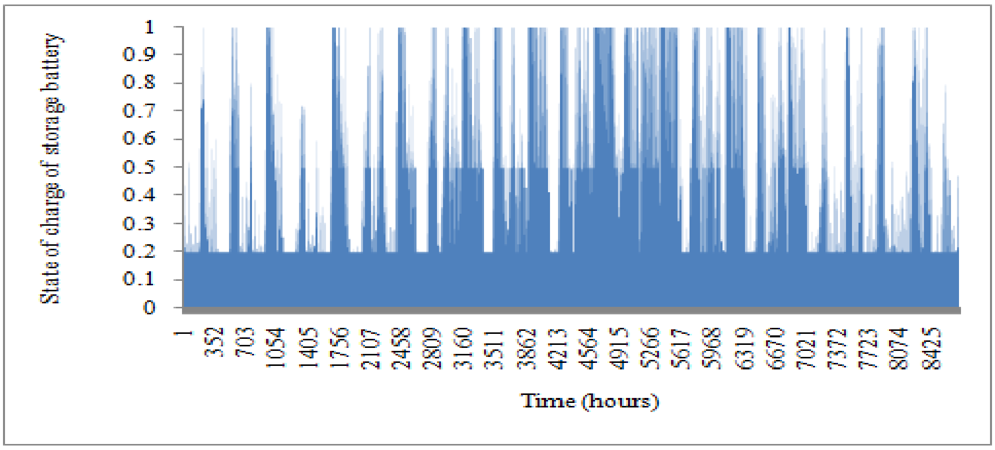


Fig. 4.13 One year hourly state of charge of storage battery at location1 for load1

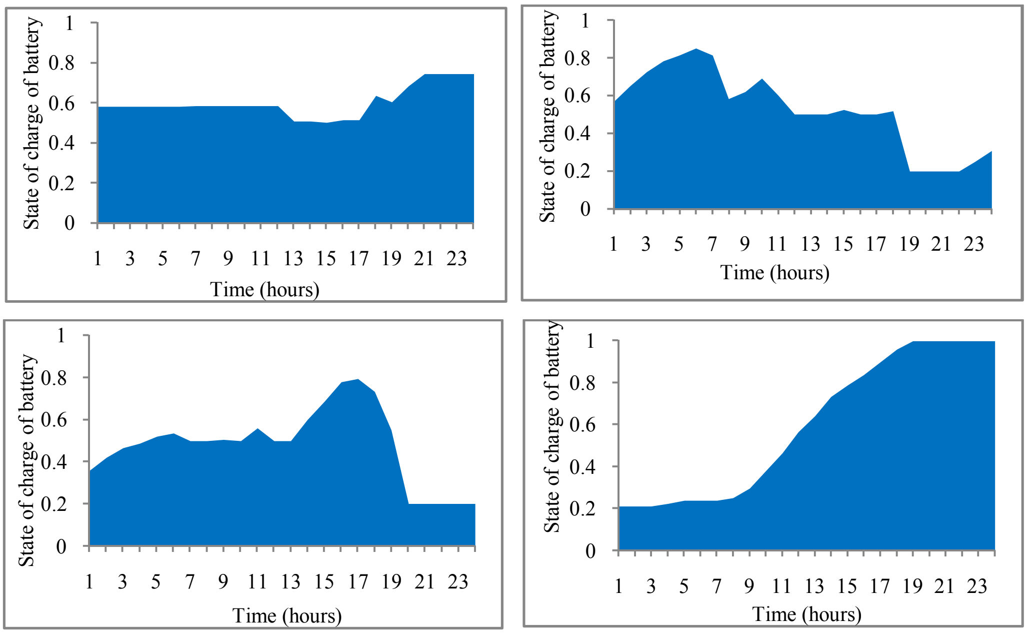


Fig. 4.14 Patterns of state of charge of battery on four typical days

Increase in average SOC of the battery ensures increase in the life span of the battery. The hourly SOC of the storage battery for one year at location1 with load1 for optimal HPS is plotted in Fig. 4.13. The minimum SOC is 20% and average SOC is 50.59%. The hourly SOC of each day is different from other due to the fluctuating nature of RE and load. SOC in four typical days are plotted in Fig. 4.14. It is to be ensured that the average SOC of battery is higher than 50%.

The percentage average SOC of the storage battery for load1 and load2 at all three locations for the optimal systems is shown in Figs. 4.15 and 4.16 respectively. The results show that except wind mill only optimal system at location3 have average SOC more than 50%. The wind mill only optimal system at location3 does not satisfy the equation (4.11) in terms of average SOC.

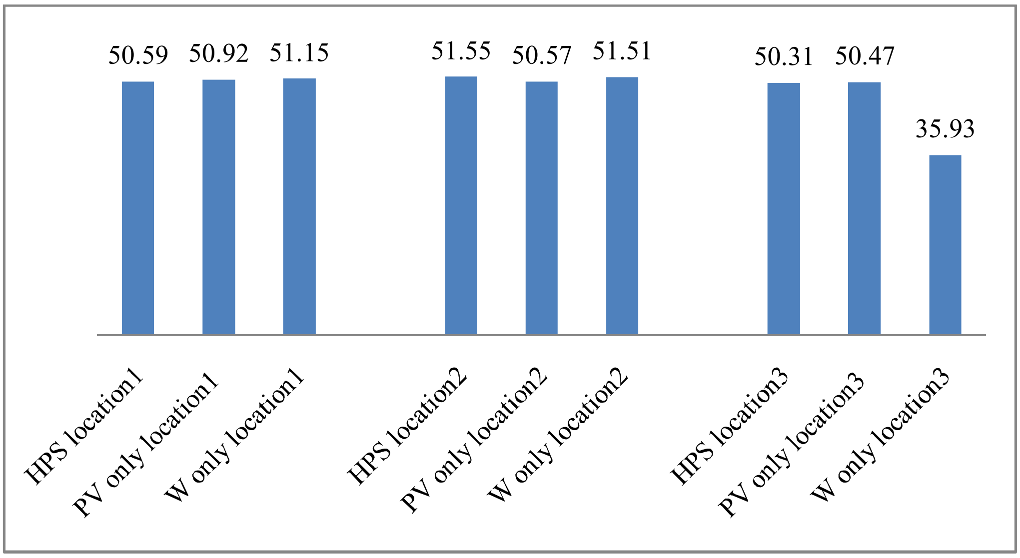


Fig. 4.15 Percentage state of charge of storage battery at three locations for load1

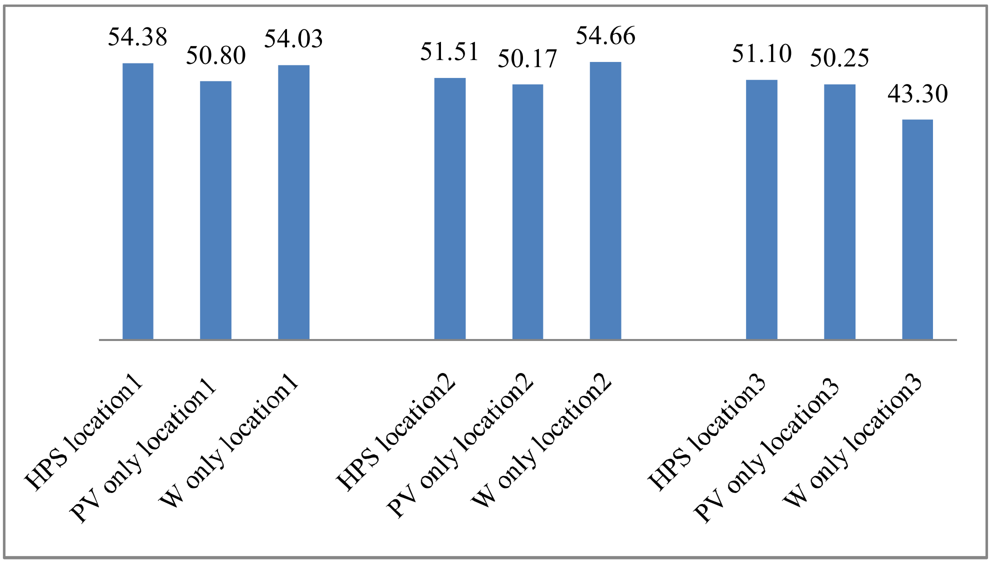
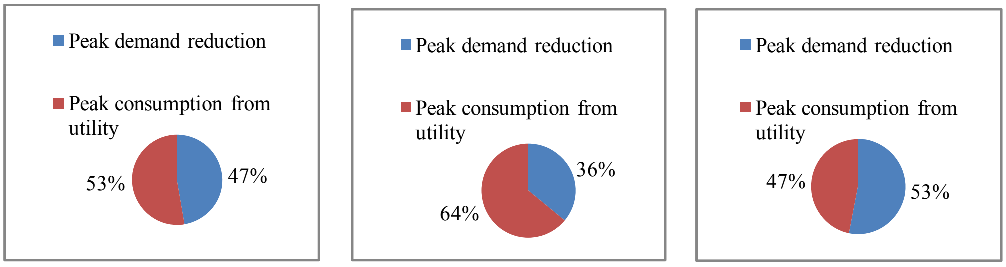


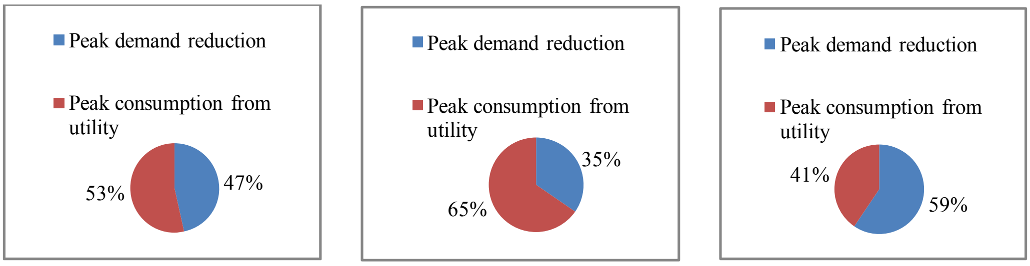
Fig. 4.16 Percentage state of charge of storage battery at three locations for load2

4.6.4 Peak demand reduction

The optimization algorithm is applied to find out the peak demand reduction of the premises. Peak demand reduction and peak consumption from the utility for both loads with three configurations are shown in Figs. 4.17, 4.18 and 4.19 for locations 1, 2 and 3 respectively. It is observed that the peak demand reduction is in the range of 35% to 55% at locations 1 and 2 for both load curves and different combination of optimal RES. However in location3 where the wind generation is low, the peak demand reduction is not as at locations 1 and 2 for wind mill only condition for load1. The reason for this is that it is unable to satisfy the constraint in terms of SOC as explained in subsection 4.6.3.

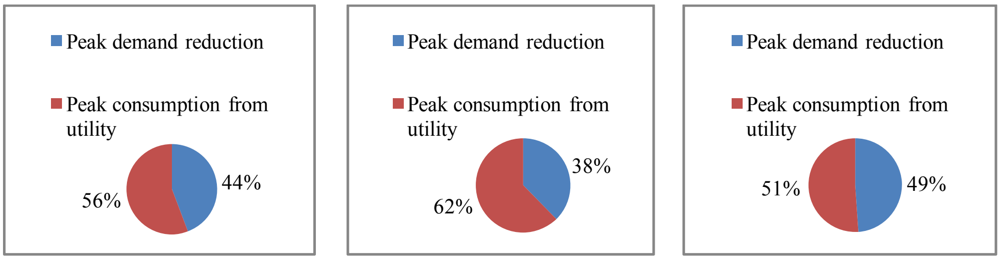


(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1

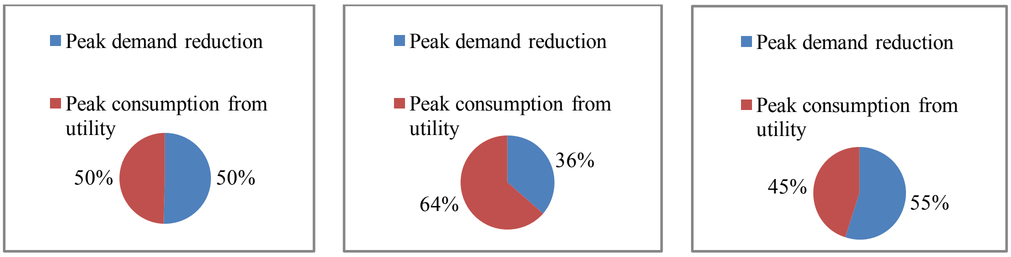


(d) HPS for load2 (e) PV only for load2 (f) Wind mill only for load2

Fig. 4.17 Peak demand reduction of premises at location1 for both loads of HPS and individual RES optimal system

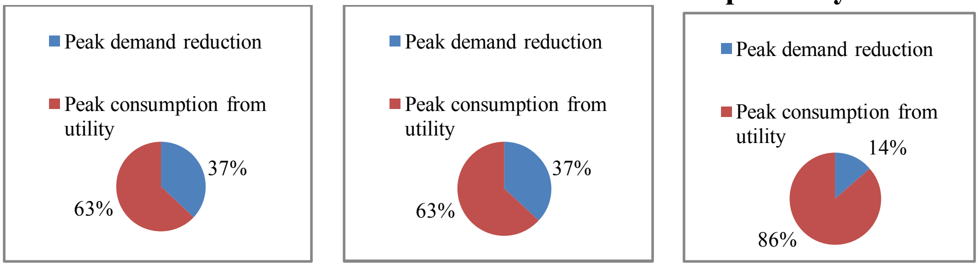


(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1

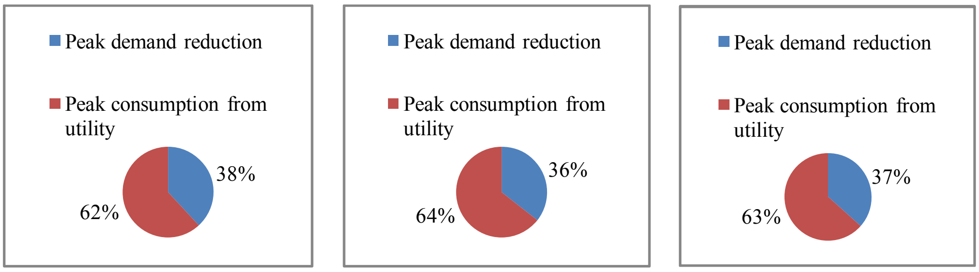


(d) HPS for load 2 (e) PV only for load 2 (f) Wind mill only for load 2

Fig. 4.18 Peak demand reduction of premises at location2 for both loads for HPS and individual RES optimal system



(a) HPS for load 1 (b) PV only for load1 (c) Wind mill only for load1



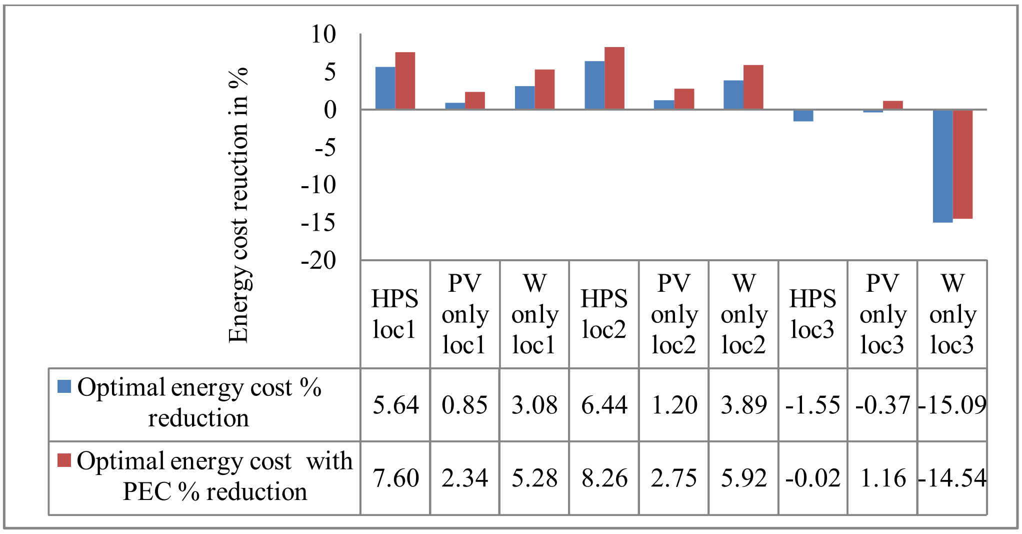
(d) HPS for load2 (e) PV only for load2 (f) Wind mill only for load2

Fig. 4.19 Peak demand reduction of premises at location3 for both loads for HPS and individual RES optimal system

The life time energy cost of the optimal system is determined by this algorithm to compare it with conventional energy cost. Comparison of combined and individual RES optimal systems is also carried out in terms of life time energy cost to determine most financially feasible system. This is discussed in the next subsection.

4.6.5 Optimal life time energy cost

The life time energy cost for optimal system for all configurations is compared with conventional energy cost in Fig. 4.20 and Fig. 4.21 at three locations for load1 and load2 respectively. The optimal energy cost with PEC is also taken into account in the comparison.

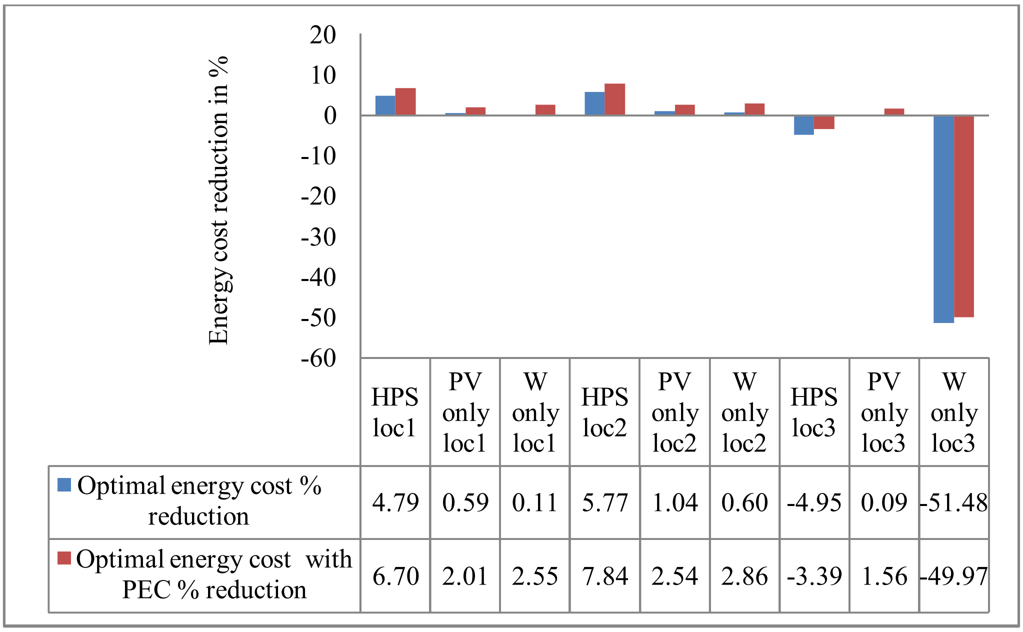


	HPS loc1	PV only loc1	W only loc1	HPS loc2	PV only loc2	W only loc2	HPS loc3	PV only loc3	W only loc3
🟦 Optimal energy cost % reduction	5.64	0.85	3.08	6.44	1.20	3.89	-1.55	-0.37	-15.09
🟥 Optimal energy cost with PEC % reduction	7.60	2.34	5.28	8.26	2.75	5.92	-0.02	1.16	-14.54

Fig. 4.20 Comparison of optimal energy cost with conventional energy cost at three locations for load1

The optimal energy cost is less for HPS for both demand profiles for location1 and location2 as seen in Figs. 4.20 and 4.21 and for location3 is PV only system in view of life time energy cost of the project. The optimal energy costs are about 5% to 6% less than conventional energy cost for optimal system for both location1 and location2. But at location3 the optimal energy cost is slightly higher than conventional energy cost for load1 and near to conventional energy cost for load2.

The PEC can be taken into account in the determination of optimal energy cost if the utility is providing this considering peak energy consumption reduction of the premises. The % reduction of optimal energy costs with PEC for all optimal systems are also shown in Figs. 4.20 and 4.21. Providing PEC reduces the optimal energy cost about 1% less than conventional energy cost for both loads at location3 for the optimal systems. So PEC is required to make conventional grid tied optimal systems financially feasible at low wind location.



	HPS loc1	PV only loc1	W only loc1	HPS loc2	PV only loc2	W only loc2	HPS loc3	PV only loc3	W only loc3
🟦 Optimal energy cost % reduction	4.79	0.59	0.11	5.77	1.04	0.60	-4.95	0.09	-51.48
🟥 Optimal energy cost with PEC % reduction	6.70	2.01	2.55	7.84	2.54	2.86	-3.39	1.56	-49.97

Fig 4.21 Comparison of optimal energy cost with Conventional energy cost at three locations for load2

Optimal system for location1 for load1 is 2.35kW PV module, 3kW wind mill, 16kW storage battery and 5kW hybrid inverter with MPPT controllers. 1.1kW PV module, 1kW wind mill, 6kW storage battery and 2kW hybrid inverter with MPPT controllers are the optimal system for same location for load2. The optimal life time energy costs for load1 and load2 at location1 are INR 102.59lakh and INR 34.79lakh respectively for location1 which are about 5% to 6% less than life span conventional energy costs of INR 108.73lakh and INR 36.54lakh respectively. If PEC is provided by the utility as described in problem formulation, the optimal energy cost is INR 100.46lakh and INR 34.089lakh for location1 with load1 and load2 respectively which are about 7% to 8% less than conventional energy cost.

At location 2, the optimal system is 2.3kW PV module 3kW wind mill, 15kW battery and 5kW inverter with MPPT controllers and for load1 and 1.2kW PV module, 1kW wind mill, 6kW storage battery and 2kW inverter with MPPT controller are the components of optimal HPS for load2. The optimal life time energy costs are INR 101.72lakh and INR 34.43lakh for load1 and load2 respectively for location2 which are also about 6% less than conventional energy costs. The optimal energy cost with PEC is INR 99.74lakh and INR 33.68lakh for load1 and load2 respectively for location2 which are about 8% less than conventional energy cost.

The optimal system for location3 and load1 is 6.8kW PV module, 16kW storage battery and 7kW inverter with MPPT controller. Optimal system for load2 at location3 is 2.25kW PV module, 5kW storage battery and 2kW inverter with MPPT controllers. The optimal energy costs are INR 109.12lakh and INR 36.51lakh for load1 and load2 respectively in which optimal energy cost for load1 is higher than conventional energy cost. The optimal energy costs with PEC are INR 107.46lakh and INR 35.97lakh for load1 and load2 respectively which are about 1% less than conventional energy cost.

HPS is recommended for locations1 and location2 and PV module is suitable for location3. The optimal energy cost may be higher than the conventional energy cost in some locations for conventional grid tied system. PEC is to be implemented by the utility to promote distributed RE generation by making the system financially feasible where the grid is single directional.

It is summarised as the RE consumed is more than 38% of the demand of the premises if optimal conventional grid tied RES system is provided in the building. So providing optimal RES reduces CO_2 emission more than 38%. There is 14% to 18% of dump load for the optimal system which can only be reduced by shifting of seasonal loads or DSM. Average SOC of the battery is more than 50% for all optimal systems. More than 35% reduction in peak load can also be achieved. The optimal energy cost at high wind locations is about 5% to 6% less than conventional energy cost. PEC may be required to make the system financially viable at low wind locations for some demand profiles. The investment cost of utilities for the conventional generators to meet the peak load can be saved if peak load reduction is achieved by promoting conventional grid tied system. Peak load reduction also makes the grid healthier.

In the next section, the sensitivity analysis is carried out on conventional energy cost and investment of components of HPS.

4.7 Sensitivity Analysis

After finding the optimal rating of the HPS based on projected cost of conventional energy, sensitivity analysis is conducted for the system developed in case of variation in energy cost and system component investment cost.

4.7.1 Changes in the cost of energy drawn from grid

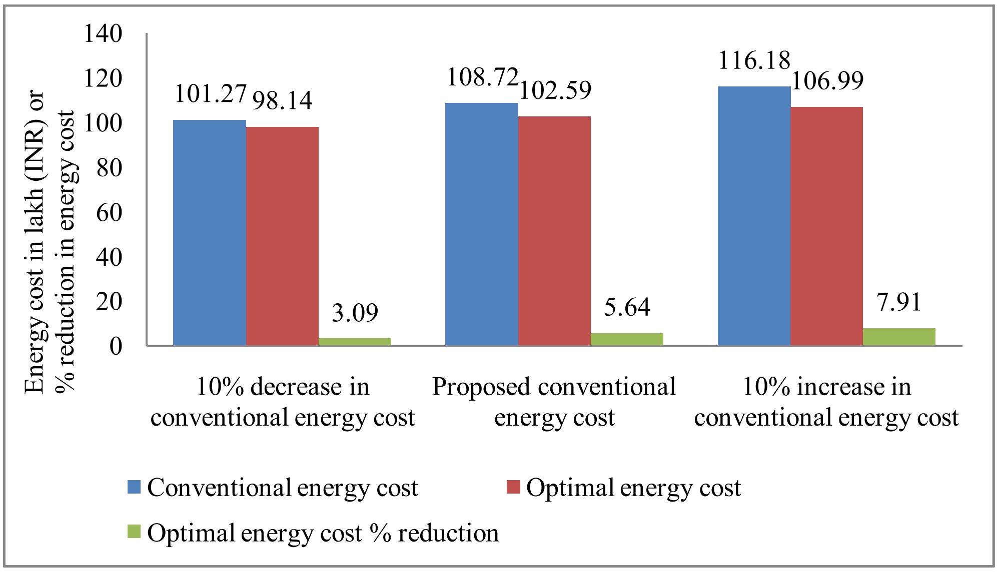


Fig 4.22 Sensitivity analysis on cost of energy drawn from grid at location1 for load1

The optimal system ratings are found out on the assumption of a variable energy cost spanning 25 years for energy drawn from grid (conventional energy cost). This cost is based on the changes in the last 5 years projected to next five years span assuming a flat increase. The exact energy cost may not be same as the projected energy cost considered for simulation. For the purpose of this work a sensitivity analysis is conducted taking into account some variation in the conventional energy cost assumed for simulation. Even though this also unpredictable to analyse, a change of 10% decrease and increase in proposed conventional energy cost is considered for sensitivity analysis.

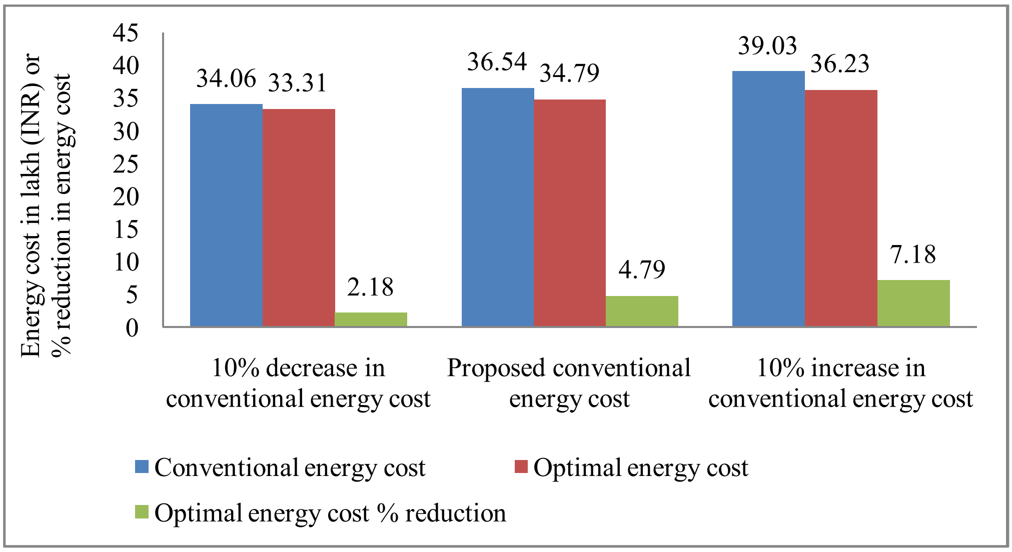


Fig 4.23 Sensitivity analysis on cost of energy drawn from grid at location1 for load2

From sensitivity analysis it is observed even under a 10% reduction in the conventional energy cost, the HPS is more economical and optimal energy cost is INR 98.14lakh for load1 at location1 and INR 33.31lakh for load2 at the same location as plotted in Figs. 4.22 and 4.23. The optimal energy cost is increasing with conventional energy cost but the percentage reduction of optimal energy cost with respect to conventional energy cost is high. So increase in conventional energy cost makes the HPS more financially feasible.

4.7.2 Change in the cost of HPS components

As explained in section 4.7.1 it is also to be envisaged that the cost of HPS components PV module, wind mill and inverter with MPPT controllers may change possible down wards. Even though, the effect of component variation on optimal energy cost is analysed by taking 10% decrease and increase in the cost of component. The results indicate that the optimal energy cost is less than conventional energy cost even 10% increase in HPS component as displayed in Fig. 4.24 and Fig. 4.25 for load1 and load2 respectively at location1.

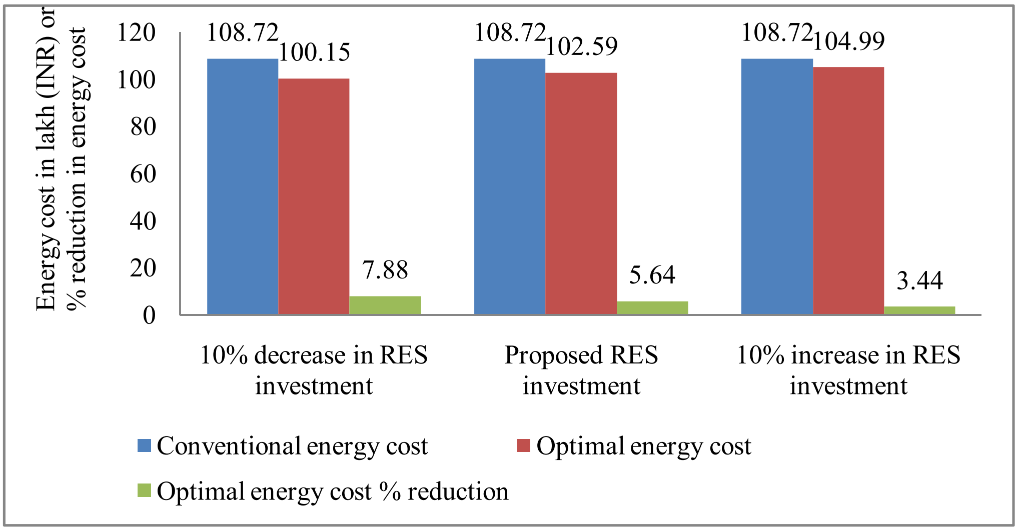


Fig 4.24 Sensitivity analysis on component of HPS investment at location1 for load1

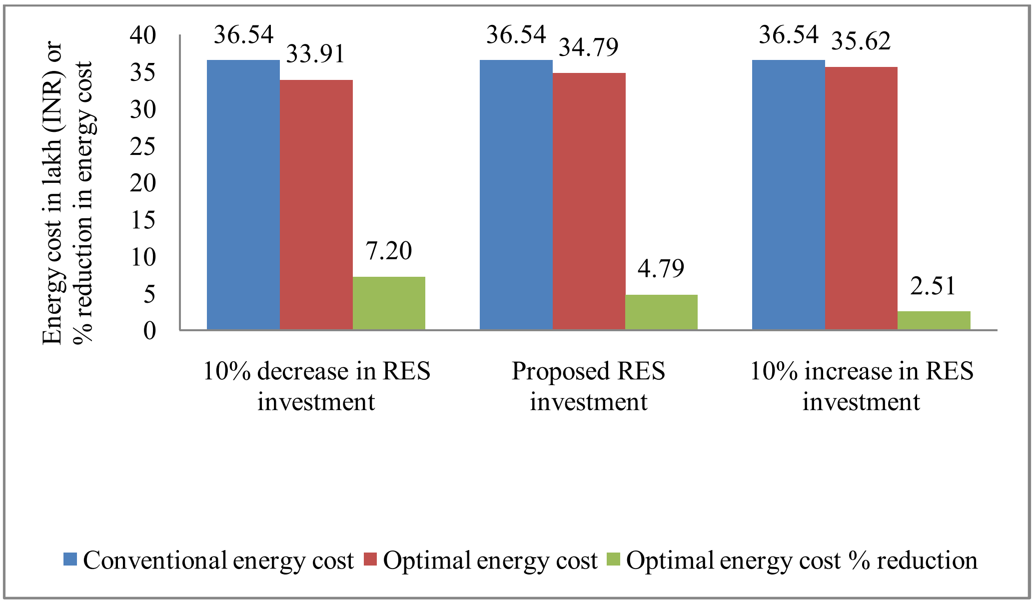


Fig 4.25 Sensitivity analysis on component of HPS investment at location1 for load2

The optimal energy cost for load1 for 10% increase in HPS components invest is INR 104.99lakh and for load2 is INR 35.62lakh. The decrease in HPS components investment makes the system more financially feasible.

4.8 Conclusion

The technical and financial models developed in chapter 3 for different components of HPS are utilised to find the economic rating of different components of HPS and savings in energy cost by developing algorithm for conventional grid tied system. Three locations are selected because of different mix of RES. Since load in the premises can be of different nature two typical load patterns are also considered for analysis. The system selected does not permit energy fed to the grid – only energy can be drawn from the grid. The ratings of components of HPS which yield minimum energy cost for the entire life time are obtained by the analysis. In addition to HPS, optimal configuration for least energy cost in the case of PV only and wind mill only condition are also found out. The RE generation, dump load and SOC of the storage battery of the optimal system are also analysed. The results show that the algorithm developed can be utilized to determine optimal system at desired location and load. It is also capable to analyse the technical, economical and environmental impact of the system.

After finding the optimal rating of the HPS based on projected cost of conventional energy, sensitivity analysis is conducted for the system developed in case of variation in energy cost and component investment. It is found that still the HPS system is economic and ratings of optimal systems are same. In chapter 5 the smart grid tied system to avoid the dump load is proposed and analysis is conducted to determine optimal system.

Chapter 5

Smart Grid Tied Hybrid Power System

5.1 Introduction

The optimal rating of RES and storage battery of a HPS with no provision for power feeding to grid, surplus energy being dumped has been explored in Chapter 4. This was tested for three locations and two load curves in each location. The demand profile of the premises and environmental condition of RES are the inputs. The development of smart grid solved most of the issues of integration of RES to grid. Grid modernization makes the grid by-directional. Then the excess RE generated in the premises can be delivered to the grid and when demand of premises is larger than RE generation the shortage can be met from the grid. This system consists of a combination of PV module and wind mill as RES is called smart grid tied HPS. In this chapter this system is modelled and algorithm is developed to determine optimal system configuration for a desired site conditions and demand profile. If the generated energy of HPS is directly fed to the grid there by investment cost of storage devices can be avoided. However this will affect peak energy charges drawn from grid when peak energy cannot be met from RES. The GEC is taken into account in problem formulation. Impact of PEC on optimal energy cost is also analysed in this work. Peak energy reduction, RE generation and CO_2 emission reduction are the factors analysed in the work as same as previous chapter.

5.2 Description of Smart Grid Tied Hybrid Power System Configuration

The PV module and wind mill DC output power is fed into grid through smart grid tied inverter with MPPT controller.

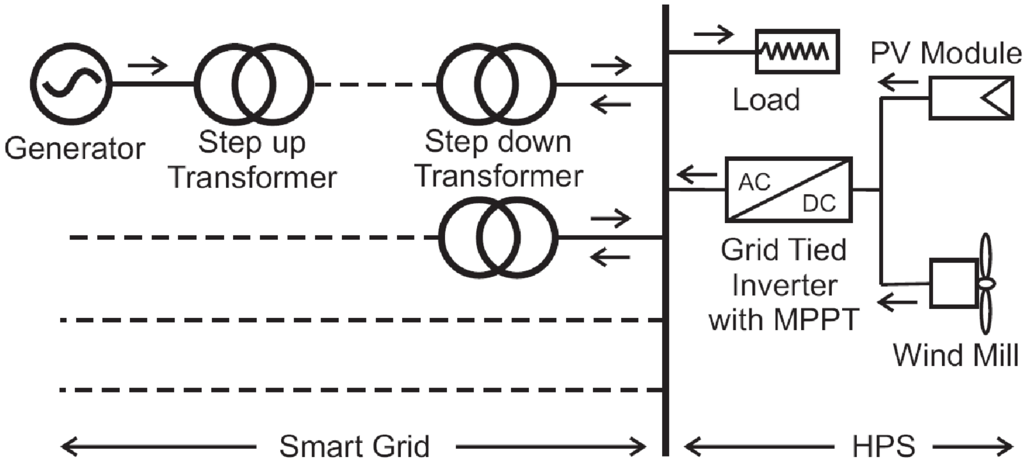


Fig. 5.1 One line diagram of smart grid tied HPS with power flow of grid

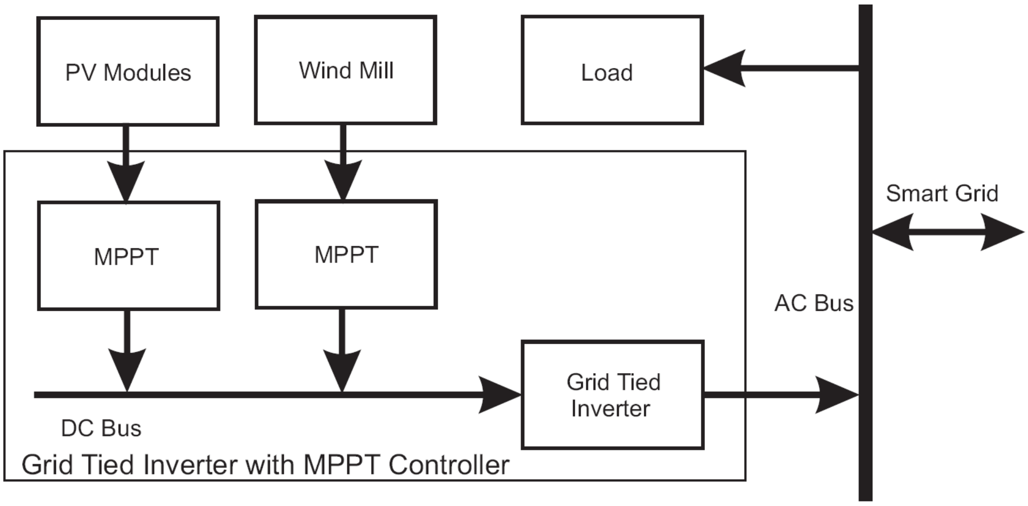


Fig. 5.2 Configuration of smart grid tied hybrid power system

The single line diagram of the system is shown in Fig. 5.1 and block diagram of the HPS with power flow of grid is shown in Fig. 5.2. The power from the RES is fed directly to grid and the load demand is met from the grid. The grid can accept power from RES or can feed the load of the premises at any time.

The MPPT for both solar and wind are connected to RES to extract maximum power from these. The smart grid tied inverter with MPPT controller cost is taken into account in the problem formulation.

5.3 Mathematical Formulation

5.3.1 Utility energy cost of smart premises

$C_{\gamma_{ij}}$ is the life time energy cost of utility energy to the smart premises which is determined as

$$C_{\gamma_{ij}} = C_{\gamma m_{ij}} + C_{\gamma o_{ij}} + C_{\gamma n_{ij}} + C_{\zeta} \tag{5.1}$$

Where

$$C_{\gamma m_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_1}^{t_2} \left[+ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) \right] * r_m \right] * \omega \tag{5.2}$$

$$C_{\gamma o_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_2}^{t_3} \left[+ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) \right] * r_o \right] * \omega \tag{5.3}$$

$$C_{\gamma n_{ij}} = \left[\sum_{d=1}^{365} \sum_{t=t_3}^{t_1} \left[+ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) \right] * r_n \right] * \omega \tag{5.4}$$

Where $C_{\gamma m_{ij}}$, $C_{\gamma o_{ij}}$ and $C_{\gamma n_{ij}}$ are life time cost of energy from grid at peak, off peak and normal hours respectively.

5.3.2 Cost of renewable energy delivered to the smart grid

$C_{\partial_{ij}}$ is annual cost of RE delivered to the utility grid in a year with PV module rating *i* and wind mill rating j.

$$C_{\partial_{ij}} = C_{\partial m_{ij}} + C_{\partial o_{ij}} + C_{\partial n_{ij}} \tag{5.5}$$

$C_{\partial m_{ij}}$, $C_{\partial o_{ij}}$ and $C_{\partial n_{ij}}$ are determined from equations (5.2) to (5.4) by substituting r_m , r_o and r_n with $r_{\partial m}$, $r_{\partial o}$ and $r_{\partial n}$ where these are unit cost of energy to grid at peak, off peak and normal hours respectively. Also negative value of $(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j})$ is the hourly energy to grid.

5.3.3 Objective function for smart premises

The rating of HPS for least energy cost has been determined by taken into account all the constraints. The energy cost is calculated for life time of the project. The objective function for smart premises to obtain optimal HPS is Minimize:

$$C_{\Phi_{ij}} = C_{s_i} + C_{w_j} + C_{v\approx_x} + C_{\varpi_{ij}} + C_{\gamma_{ij}} - C_{\mu\approx_{ij}} - C_{\partial_{ij}} \tag{5.6}$$

Where $C_{\Phi_{ij}}$ is the energy cost of smart premises for life span of the project with PV module rating i and wind mill rating j . $C_{v\approx_x}$, $C_{\varpi_{ij}}$ and $C_{\mu\approx_{ij}}$ are the net investment of smart grid tied inverter of *x* rating, cost of smart meter and GEC for smart grid tied system for *i* rating of PV module and *j* rating of wind mill respectively.

5.3.4 Constraints of smart premises

Constraints are applied to obtain most suitable HPS to ensure stability and reliability of grid. Output power from RES fluctuates depending upon weather condition. This will affect the quality of grid power. The maximum penetration ratio of RES is to be limited to maintain the quality of grid [116], [127]. Studies shows that maximum penetration ratio of passive PV generators in European island is 30% [111]. Also the cost of energy delivered to the grid depends on the grid conditions [136].

However as RE generation in India is only picked up slowly, for the purpose of this work , maximum available energy to grid is limited to a higher value than 30% (Λ %) of average consumption of the premises at off peak hours and normal hours. Λ value is decided based on local condition. These are expressed as

$$E_{o\partial_{ij}} \leq \frac{\sum_{d=1}^{365}\sum_{t=t_2}^{t_3} Pl_{dt} * \Lambda}{100} \tag{5.7}$$

$$E_{n\partial_{ij}} \leq \frac{\sum_{d=1}^{365}\sum_{t=t_3}^{t_1} Pl_{dt} * \Lambda}{100} \tag{5.8}$$

Where $E_{o\partial_{ij}}$ and $E_{n\partial_{ij}}$ are off peak and normal hours energy delivered to grid. These are found as

$$E_{o\partial_{ij}} = \sum_{d=1}^{365}\sum_{t=t_2}^{t_3} |\text{-ve value of}(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j})| \tag{5.9}$$

$$E_{n\partial_{ij}} = \sum_{d=1}^{365} \sum_{t=t_3}^{t_1} |-\text{ve value of}\,(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j})| \qquad (5.10)$$

Minimum RE generation is taken as one of the inequality constraints which is described in equation (4.7) in chapter 4. Minimum and maximum ratings of PV module and wind mill are limited according to minimum capacity of RE power plant and demand of the premises. Minimum rating is least rating of each RES. Maximum rating of these are fixed such that the RE generated by individual in a year must be less than or equal to one year demand of the premises. These are described as equations (4.13) and (4.14).

5.4 Simulation

The optimal rating of HPS is found out for least energy cost of the consumer for the life span of the project. The components of HPS are modelled and input data are fed into the model. The input data are hourly solar irradiance, temperature of the PV cell and wind speed obtained as described in section 4.4 for one year. The smart grid is connected to the premises to draw shortage of power from grid and to deliver excess energy generated by the RES to the grid. The values of constants used for the simulation are shown in table 4.1.

The excess energy generated in the premises in a year is E_{ij} which is expressed in equation (4.26) in chapter 4. If E_{ij} is positive the RE generated in a year is less than one year demand of the premises. It should not be negative to satisfy one constraint i.e., to fix the maximum rating of RES.

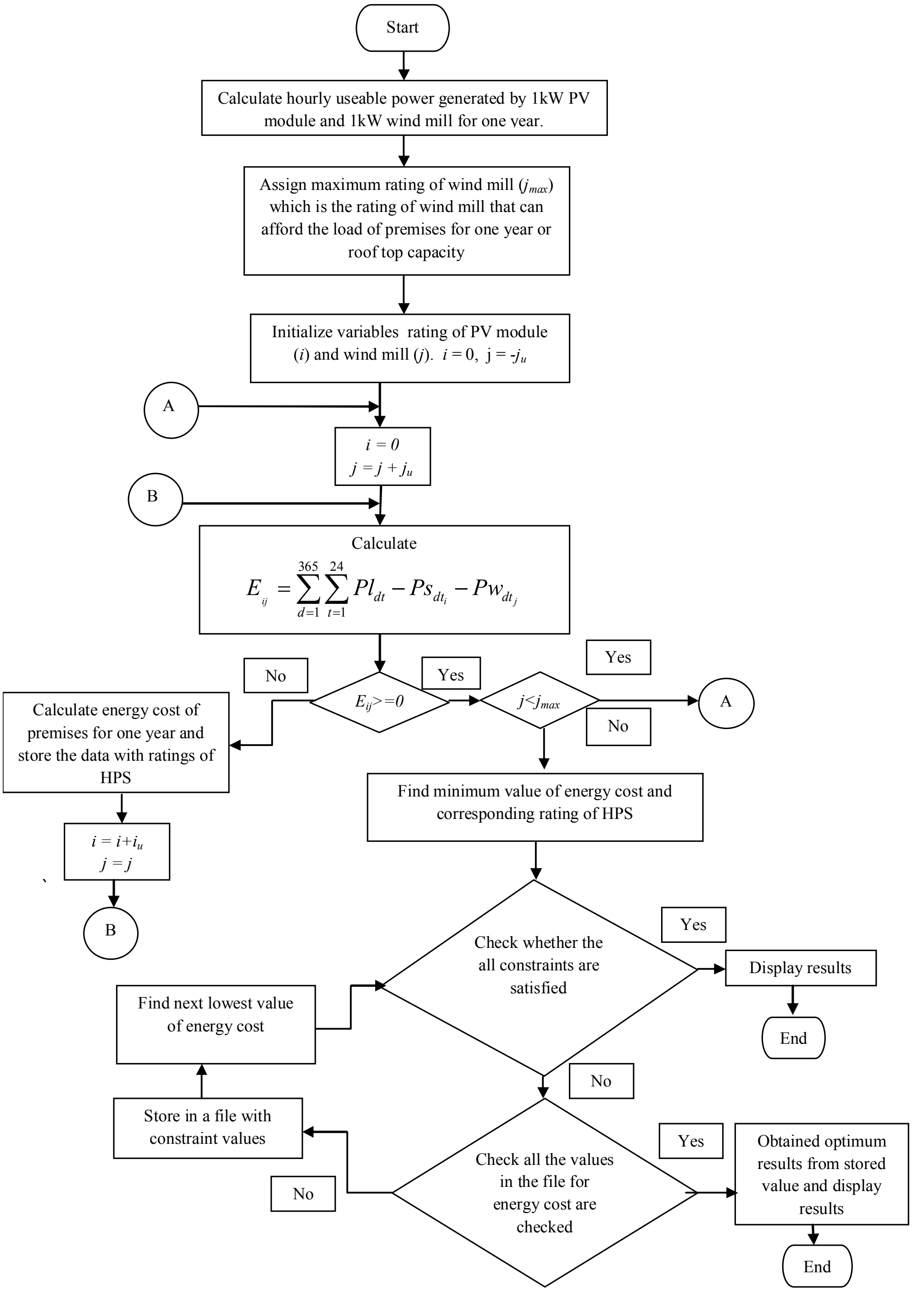


Fig. 5.3 Optimization flow chart of smart grid tied system

The life time energy cost for the premises is determined for all combinations of HPS by incrementing the rating PV module by i_u and wind mill by j_u. The optimal rating of HPS for minimum energy cost has been found out which satisfy all constraints. The simulation flow chart is shown in Fig. 5.3. The same procedure is repeated for PV only and wind mill only conditions to determine optimal system for individual RES.

5.5 Analysis

The model is applied at three locations as same as conventional grid tied HPS as in Chapter 4. In each location two types of loads are considered with different annual consumption of energy. The optimal system configurations are determined for location1, location2 and location3 for the different loads. The analysis is also conducted for individual RES systems. The solutions for the objective function as rating of optimal HPS and individual RES systems are tabulated in Table 5.1.

Table 5.1 Optimal of HPS and individual RES of smart grid tied system

Particulars	**Unit**	**Load1**			**Load2**		
		HPS	PV only	W only	HPS	PV only	W only
Location 1	kW	PV-1.10 *W-7.00 **IC-8.00	PV-7.45 IC-7.00	W-7.00 IC-7.00	PV-0.70 W-2.00 IC-3.00	PV-2.45 IC-2.00	W-2.00 IC-2.00
Location 2	kW	PV-3.40 W-6.00 IC-9.00	PV-7.35 IC-7.00	W-6.00 IC-6.00	PV-1.10 W-2.00 IC-3.00	PV-2.45 IC-2.00	W-2.00 IC-2.00
Location 3	kW	PV-7.80 W-1.00 IC-9.00	PV-7.90 IC-8.00	W-5.00 IC-5.00	PV-2.50 W-1.00 IC-4.00	PV-2.50 IC-3.00	W-2.00 IC-2.00

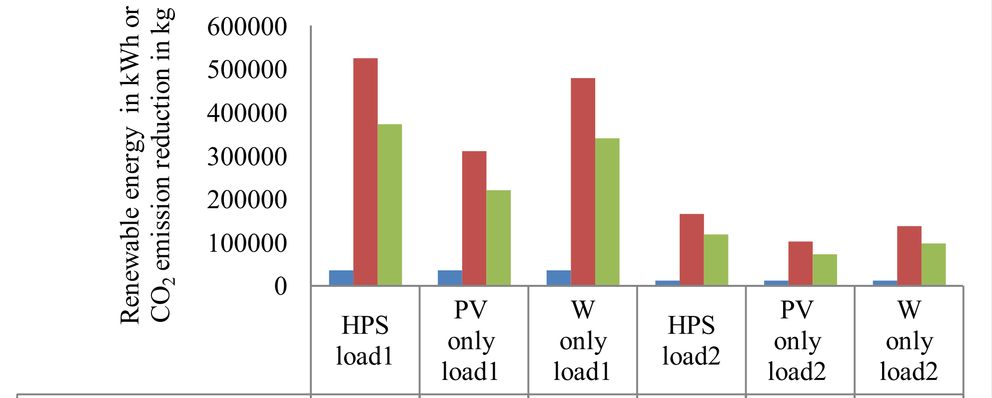
*W=Wind mill **IC=Grid tied inverter with MPPT controller

5.6 Results and Discussion

Having obtained the rating of components of HPS and individual RES for obtaining optimal operation the discussion on RE generation, peak load reduction and optimal energy cost are to be done at all three locations and two different demand curves.

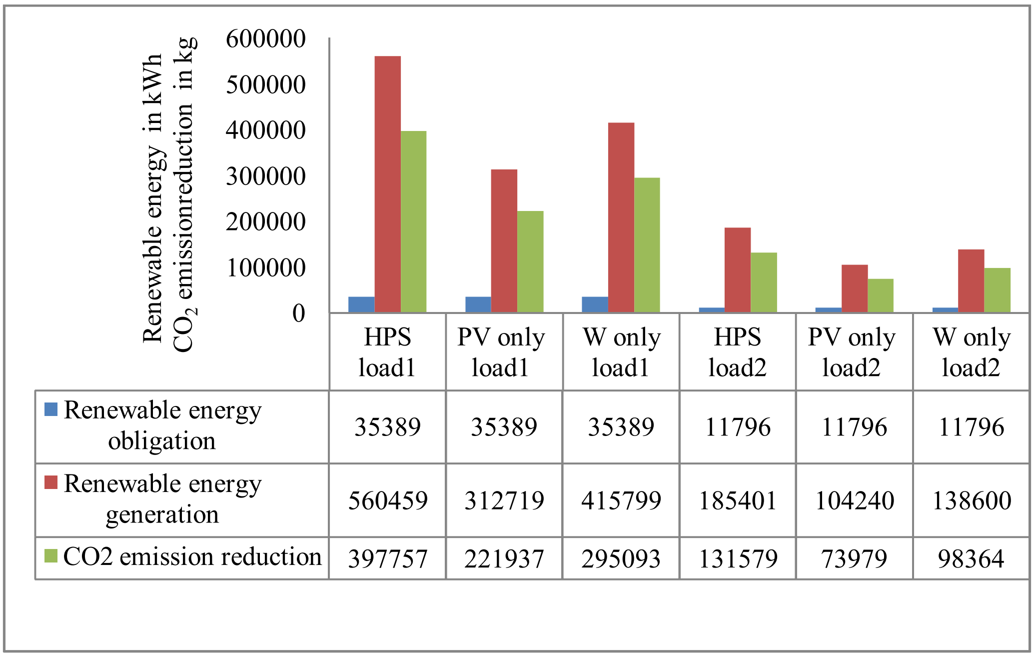
5.6.1 Renewable energy generation

The RE generation and CO_2 emission reduction is plotted with REO for combined and individual RES for load 1 and 2 in Fig. 5.4 for location1. The same factors for location2 and location3 are shown in Fig. 5.5 and Fig. 5.6 respectively. The RE generation by the optimal system both combined and individual RES is much higher than the REO of the premises for both load1 and load2 in all the locations.



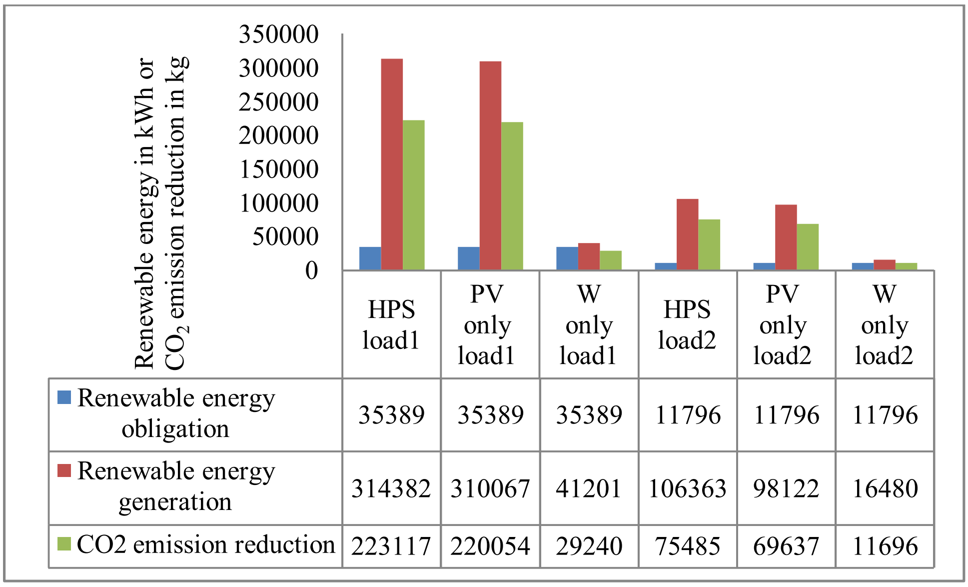
	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy generation	525946	311090	480014	166377	102305	137147
🟩 CO2 emission reduction	373264	220781	340666	118078	72606	97333

Fig. 5.4 Renewable energy obligation, renewable energy generation and CO_2 emission reduction at location1



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy generation	560459	312719	415799	185401	104240	138600
🟩 CO2 emission reduction	397757	221937	295093	131579	73979	98364

Fig. 5.5 Renewable energy obligation, renewable energy generation and CO_2 emission reduction at location2



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy generation	314382	310067	41201	106363	98122	16480
🟩 CO2 emission reduction	223117	220054	29240	75485	69637	11696

Fig. 5.6 Renewable energy obligation, renewable energy generation and CO_2 emission reduction at location3

The percentage of RE generation with respect to demand of the premises for three locations for individual and combined RES is shown in Figs. 5.7 and 5.8 for load1 and load2 respectively. The RE generation and CO_2 emission reduction are high for optimal HPS for both loads in all locations compared to PV only and wind mill only condition. At location3, optimal PV only condition also have higher RE generation and CO_2 emission reduction which is nearer to the value for optimal HPS in the same location for both loads.

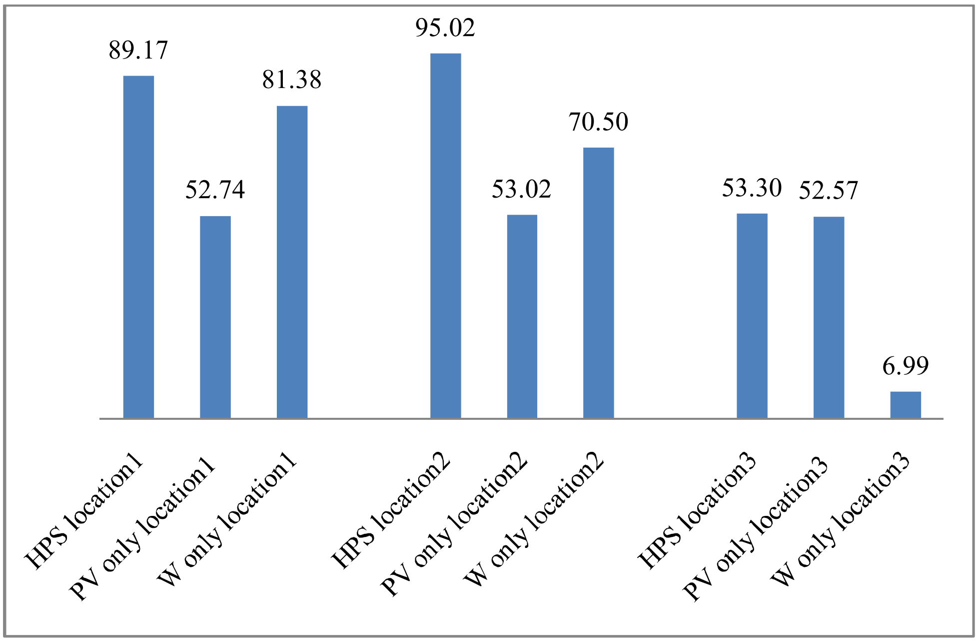


Fig. 5.7 Percentage renewable energy consumption at three locations for load1

The other factor analysed in this work is the RE to grid. This is to be within limit to ensure the reliability of the grid. The RE to grid is displayed in Fig. 5.9 and Fig. 5.10 for all three locations with load 1 and load2 respectively. It is high for optimal HPS for all locations and loads satisfying the constraint to limit the RE to grid at normal and off peak hours. At location 3 PV only optimal system also has high penetration of RE to grid. In the next sub section describes about peak demand reduction due to RE generation.

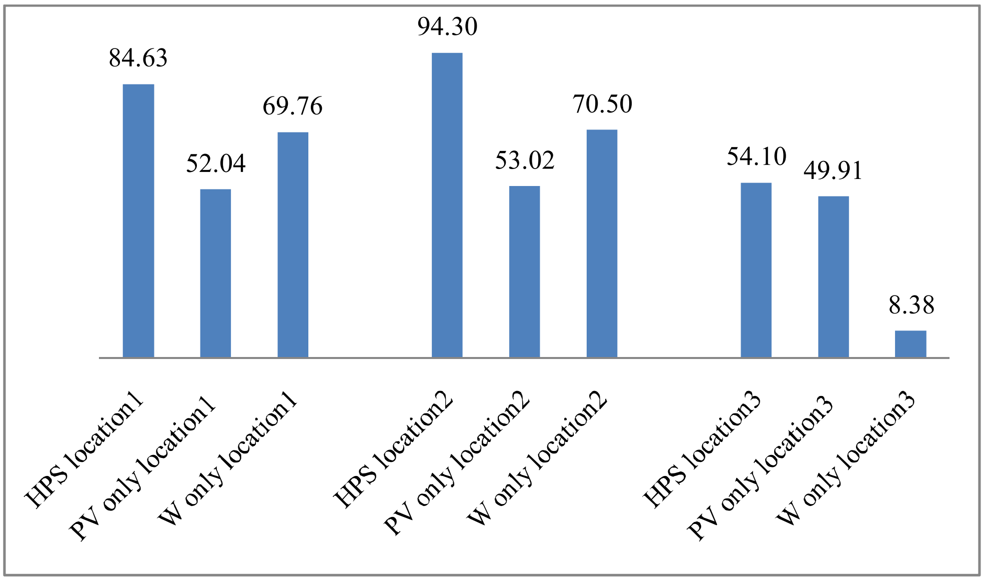


Fig. 5.8 Percentage renewable energy consumption at three locations for load2

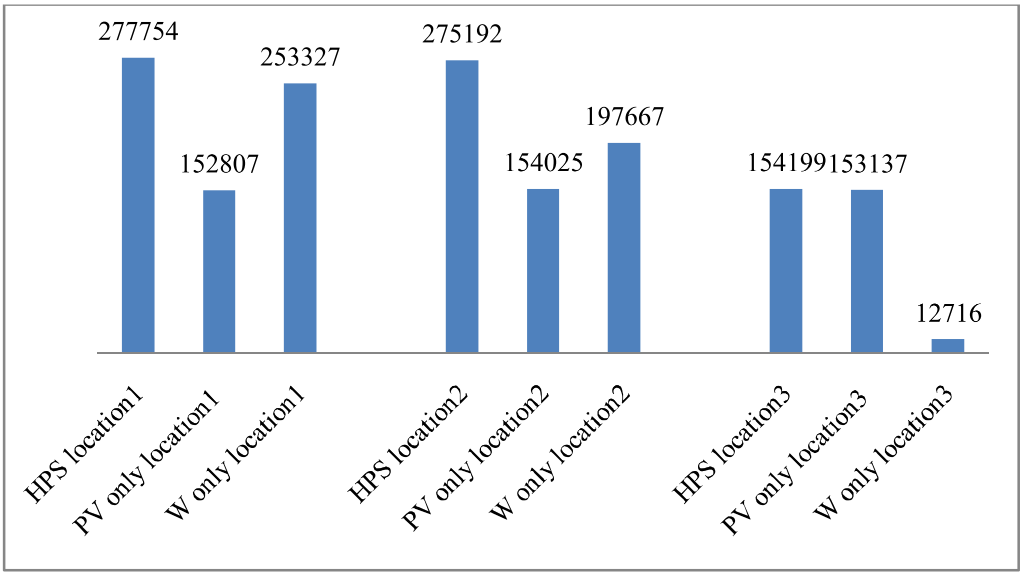


Fig. 5.9 Renewable energy to grid in kWh at three locations for load1

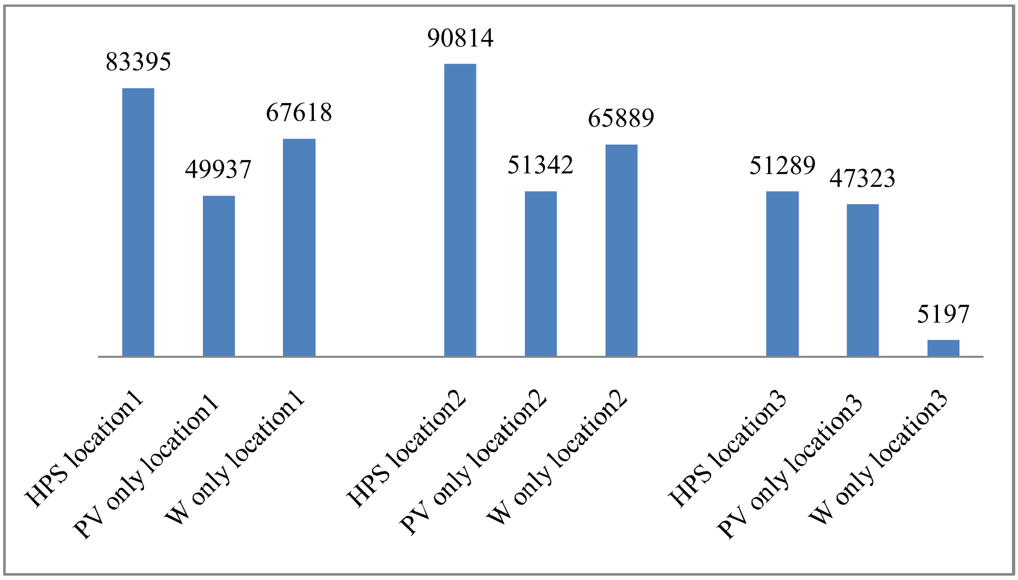
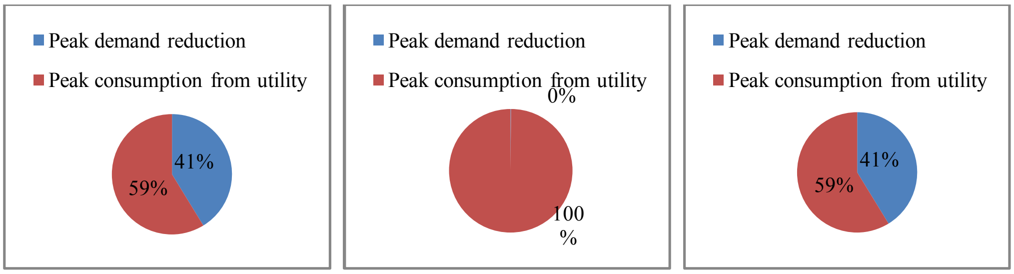
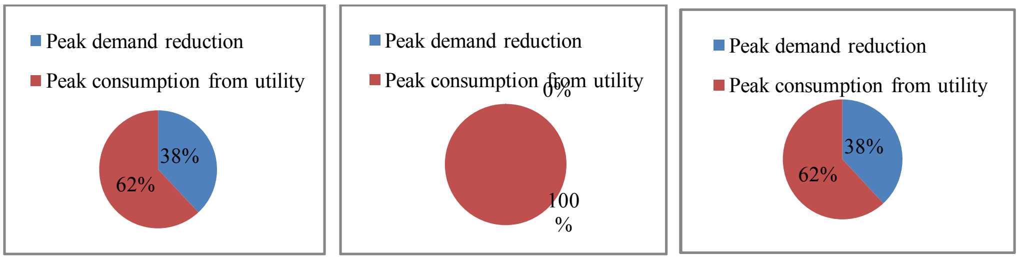


Fig. 5.10 Renewable energy to grid in kWh at three locations for load2

5.6.2 Peak demand reduction



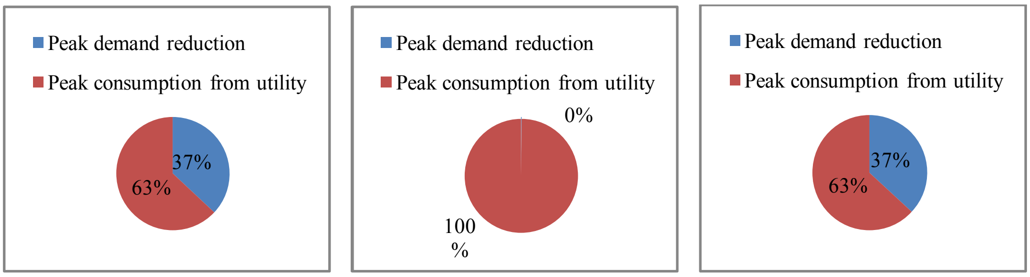
(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1



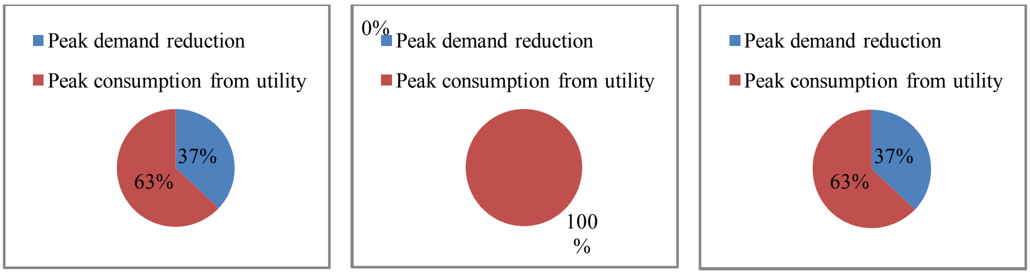
(a) HPS for load2 (b) PV only for load2 (c) Wind mill only for load2

Fig. 5.11 Peak demand reduction of premises for both loads at location1

Peak demand reduction and peak consumption from the utility for both loads are displayed in Figs. 5.11, 5.12 and 5.13 for locations1, locatiion2 and location3 respectively. Peak demand reduction is high for HPS and wind mill only optimal system for all loads and locations. PV only optimal systems have less peak demand reduction for all loads and locations. Also at location3, the peak demand reduction is very small for both loads with HPS and wind mill optimal systems. More than 37% peak demand reduction is obtained for HPS and wind mill only optimal system for all loads at location1 and location2 only in the case of smart grid tied system.



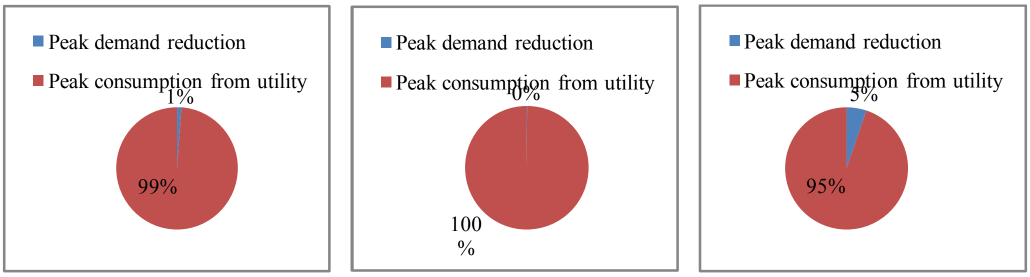
(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1



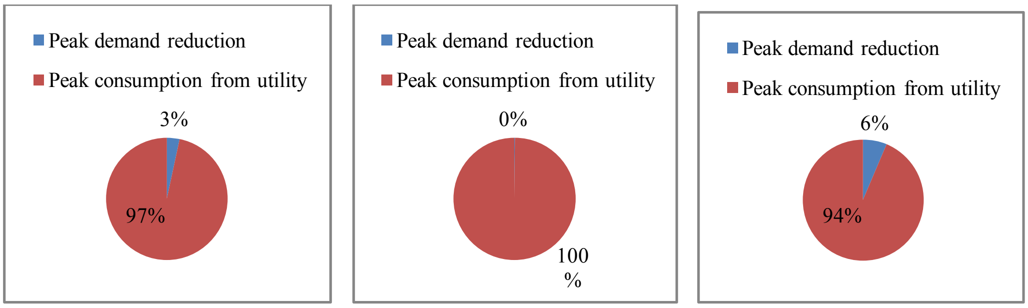
(a) HPS for load 2 (b) PV only for load 2 (c) Wind mill only for load 2

Fig. 5.12 Peak demand reduction of premises for both loads at location2

The life time energy cost of the optimal system is determined in this algorithm to compare it with conventional energy cost. Comparison of combined and individual RES optimal systems is also carried out in terms of life time energy cost to determine most financially feasible system. This is discussed in the next subsection.



(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1



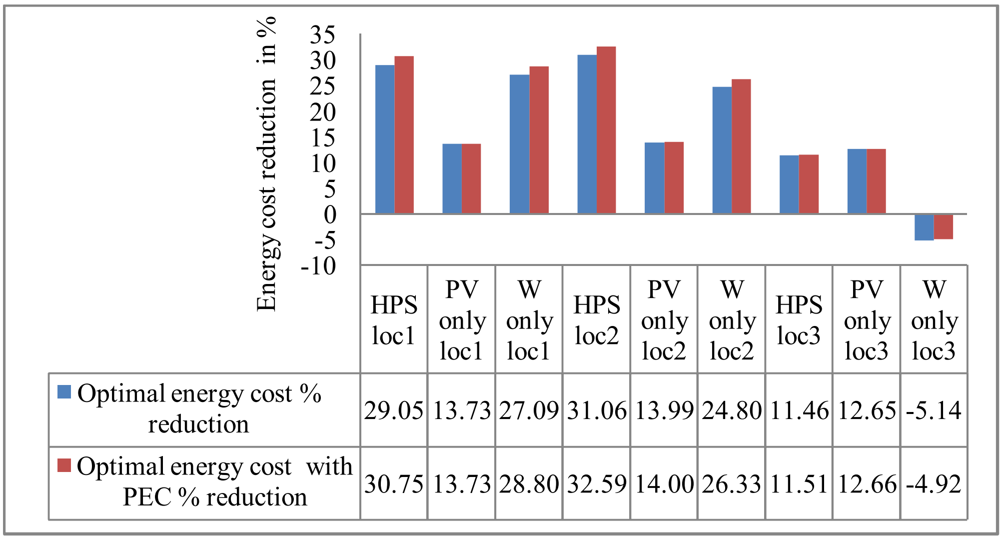
(a) HPS for load2 (b) PV only for load2 (c) Wind mill only for load2

Fig. 5.13 Peak demand reduction of premises for both loads at location3

5.6.3 Optimal life time energy cost

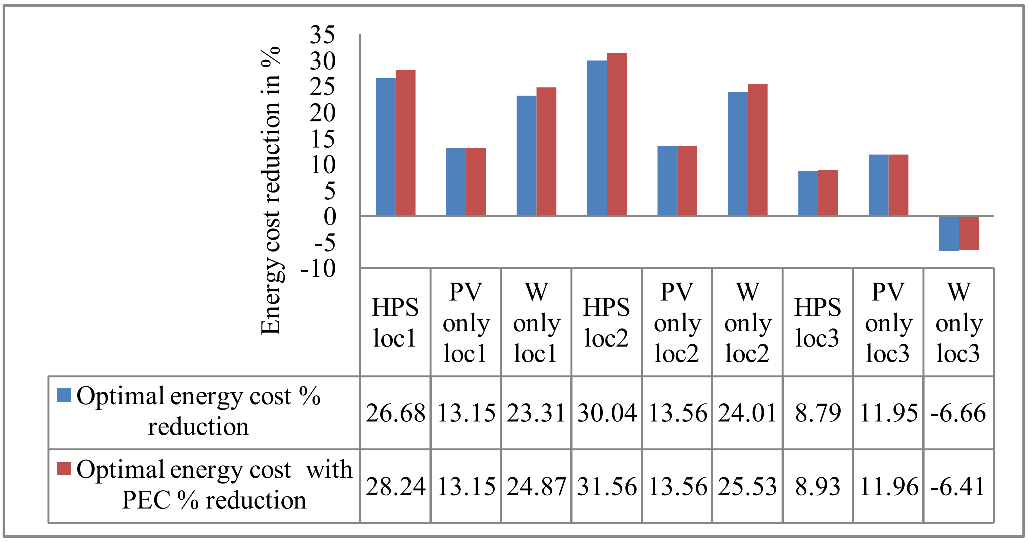
The Figs. 5.14 and 5.15 show the comparison of optimal life time energy cost of combined and individual RES system with conventional energy cost in three locations for load1 and load2 respectively. The optimal energy cost with PEC is also taken into account in the comparison.

The life time energy cost is less for optimal HPS at location1 and location2 as seen in Figs. 5.14 and 5.15 which are about 27% to 31% less than conventional energy cost. So the optimal HPS at location1 for load1 is 1.1kW PV, 7kW wind mill and 8kW inverter with MPPT controller and for load2 is 0.7kW PV, 2kW wind mill and 3kW inverter with MPPT controller. The optimal energy costs are INR 77.14lakh and INR 26.79lakh for load1 and load2 respectively. These are about 29% and 31% less than conventional energy costs of INR 108.72lakh and INR 36.54lakh for load1 and load2 respectively.



	HPS loc1	PV only loc1	W only loc1	HPS loc2	PV only loc2	W only loc2	HPS loc3	PV only loc3	W only loc3
🟦 Optimal energy cost % reduction	29.05	13.73	27.09	31.06	13.99	24.80	11.46	12.65	-5.14
🟥 Optimal energy cost with PEC % reduction	30.75	13.73	28.80	32.59	14.00	26.33	11.51	12.66	-4.92

Fig. 5.14 Comparison of optimal energy cost with conventional energy cost at three locations for load1



	HPS loc1	PV only loc1	W only loc1	HPS loc2	PV only loc2	W only loc2	HPS loc3	PV only loc3	W only loc3
🟦 Optimal energy cost % reduction	26.68	13.15	23.31	30.04	13.56	24.01	8.79	11.95	-6.66
🟥 Optimal energy cost with PEC % reduction	28.24	13.15	24.87	31.56	13.56	25.53	8.93	11.96	-6.41

Fig. 5.15 Comparison of optimal energy cost with conventional energy cost at three locations for load2

The Optimal HPS for load1 at location2 is 3.40 kW PV, 6kW wind mill and 9kW inverter with MPPT controller. The optimal energy cost is INR 74.95lakh which is about 27% less than conventional energy cost. The optimal HPS for load2 is 1.1kW PV module, 2kW wind mill and 3kW inverter with MPPT controllers. The optimal life time energy cost is INR 25.56lakh which is about 30% less than conventional energy cost.

Least optimal energy cost at location3 for both loads is obtained for PV module only system. So PV module system is suitable for location3. The optimal rating for load1 is 7.9kW PV module and 8kW inverter with MPPT controllers and for load2 is 2.5kW PV module and 3kW inverter with MPPT controllers. The optimal energy costs for load1 and load2 are INR 94.97lakh and INR 32.17lakh respectively which are about 12% less than conventional energy cost. Since the location3 is low wind location, the optimal energy cost for wind mill only condition is higher than conventional energy cost for both load1 and load2.

The optimal life time energy cost with PEC is about 28% to 32% less than conventional energy cost for optimal HPS for both locations1 and location2 and which is about 12% less for PV only system at location3 as same as optimal life time energy cost. HPS is recommended for location1 and location2 and PV module is suitable for location 3 with configurations as shown in table 5.1. In all 6 cases the least optimal energy cost is less than conventional energy cost. So RES are financially viable in a building if optimal smart grid tied systems are provided. PEC has not influence in the optimal energy cost at location3 for smart grid tied system since the peak load reduction is near to zero.

It is summarised that optimal smart grid tied systems reduce consumption from grid about more than 84% of demand in high wind locations and more than

53% at low wind locations. This same reduction in CO_2 emission is obtained due to RE generation. Peak demand reduction for optimal system at high wind locations is between 37% and 41% and at low wind location it is near to zero. Providing optimal RES in smart premises reduce energy cost about 27% to 31% at high wind locations and nearer to 12% at low wind location.

In the next section, the sensitivity analysis is carried out on cost of energy drawn from grid and investment of components of HPS.

5.7 Sensitivity Analysis

The optimization is carried out in this work based on prevailing tariff for energy purchased from grid and cost of different HPS components. However these costs are likely to change over a period of time during the project life time. Even though changes in the cost can not be predicted accurately, the most suitable assumptions are made to incorporate the variation in determining cost for the life span of the project. Even though a sensitivity analysis is conducted for a variation in the assumed cost in both directions to check the rating of optimal system is accurate and optimal energy cost is acceptable.

5.7.1 Changes in the cost of energy drawn from grid

A sensitivity analysis is conducted taking into account some variation in the conventional energy cost assumed for simulation as subsection 4.7.1. A change of 10% decrease and increase in proposed conventional energy cost is considered for sensitivity analysis in the change of energy cost drawn from grid.

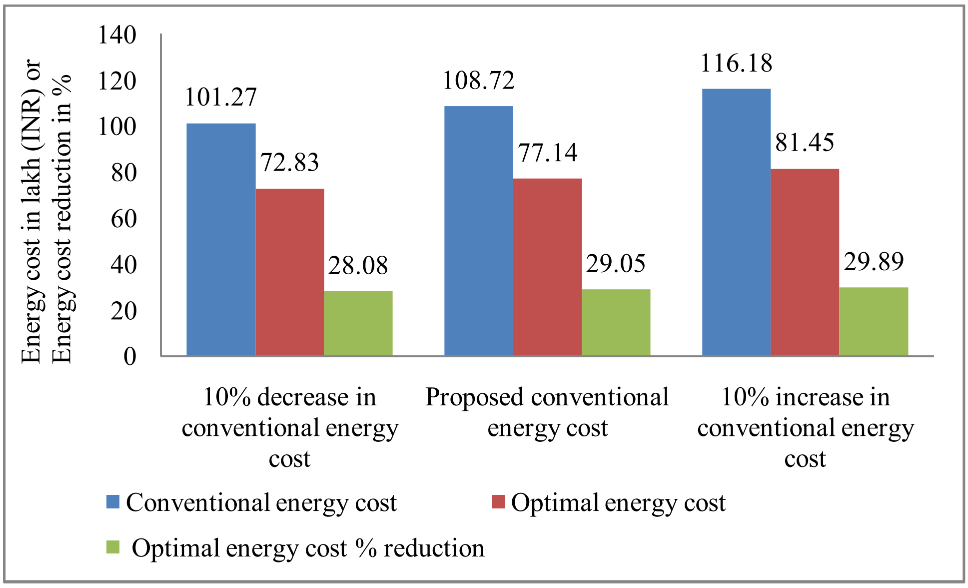


Fig. 5.16 Sensitivity analysis on cost of energy drawn from grid for load1 at location1

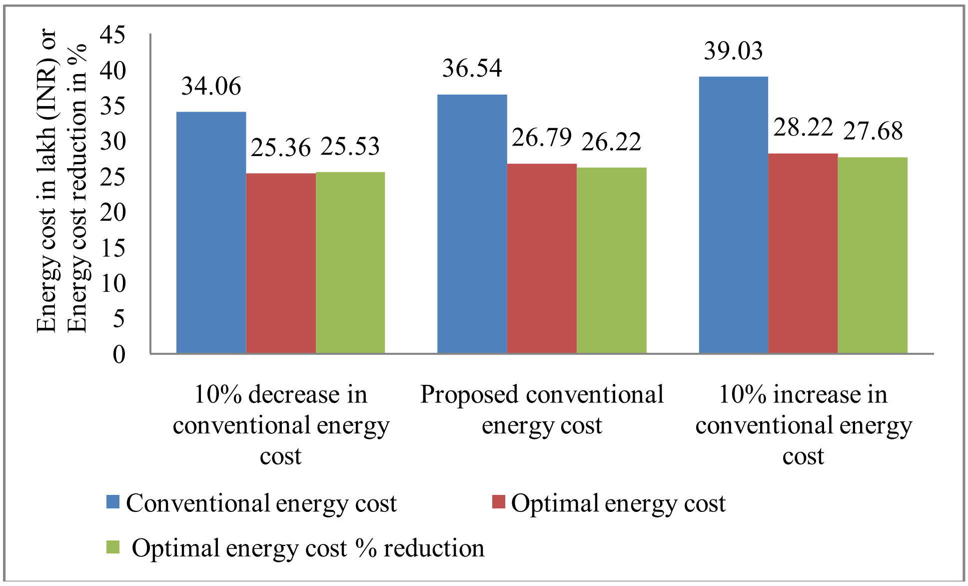


Fig. 5.17 Sensitivity analysis on cost of energy drawn from grid for load2 at location1

From sensitivity analysis it is observed even under a 10% reduction in the conventional energy cost, the HPS is more economical and optimal energy cost is INR 72.83lakh for load1 at location1 and INR 25.36lakh for load2 at the same location as shown in Fig. 5.16 and Fig. 5.17. The optimal energy cost is increasing with conventional energy cost but the % reduction of optimal energy cost with respect to conventional energy cost is high. So increase in conventional energy cost makes the HPS more financially feasible.

5.7.2 Change in the cost of HPS components

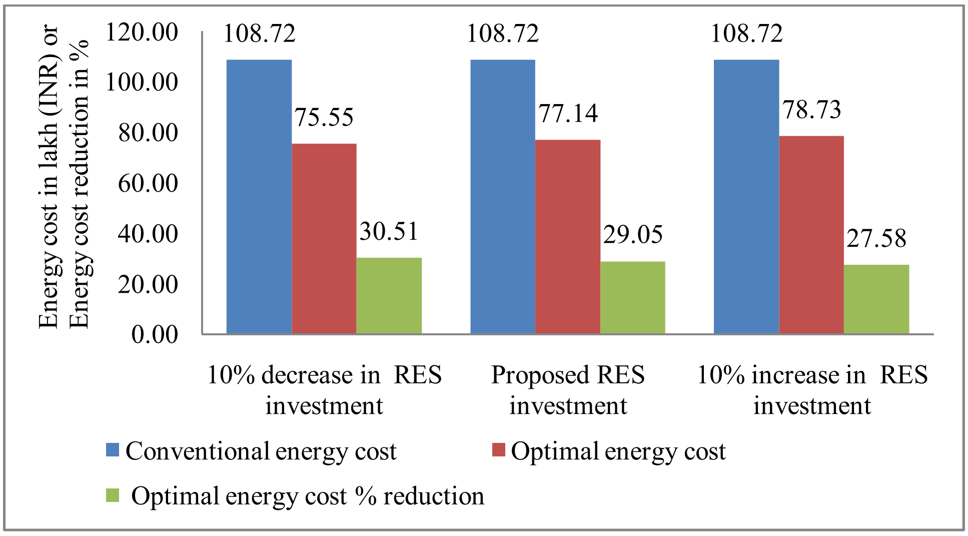


Fig. 5.18 Sensitivity analysis on component of HPS investment for load1 at location1

The effect on optimal energy cost due to variation in the cost of HPS component by taking 10% decrease and increase in the cost of component are analysed in this section. The results are displayed in Fig. 5.18 and Fig. 5.19 which indicate that optimal energy cost due to the increase in cost of HPS component is less than conventional energy cost even though it is increased compared to proposed RES investment. Most probably the cost of HPS component will reduce in future. The decrease in component cost reduces the optimal energy cost and makes the system more financially viable.

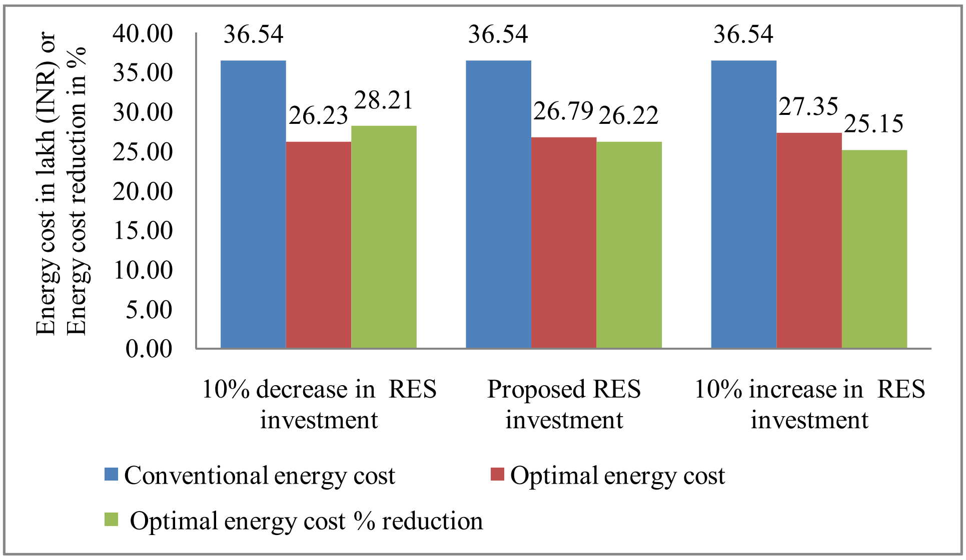


Fig. 5.19 Sensitivity analysis on component of HPS investment for load2 at location1

5.7 Conclusion

In this chapter smart grid tied HPS is modelled to determine optimal HPS consisting of PV modules, wind mill together with smart grid tied inverter equipped with MPPT controllers. The grid is capable of receiving or delivering energy when required, based on demand of premises. The objective function is developed with constraints based on economical and technical factors. The algorithm is developed to determine the composition of optimal system. This algorithm is applied to three different locations where solar irradiance and wind speed are different during a year. Each location is considered to have two different types of load. The optimal rating of HPS for least energy cost of the premises for the life span of the project is determined satisfying constraints. In addition to HPS, optimal configuration for least energy cost in the case of only one of RES namely PV only and wind mill only condition are also found out. The results show that the proposed algorithm is capable to determine optimal configuration of smart grid tied HPS and optimal life time energy cost at desired location and demand profile. It is also analysed technical, economical and environmental factors of smart grid tied system.

Sensitivity analysis is conducted for the system developed in case of variation in energy cost and investment cost of components. This is to find out whether the cost of optimal system will hold even if there is an upward as well as downward revision of 10% in conventional energy cost. It is found that still the HPS system is economic. Peak energy demand can be met by having storage battery which requires investment. This aspect is discussed in Chapter6.

Chapter 6

Smart grid tied hybrid power system with storage

6.1 Introduction

In chapter 5 optimization of HPS without energy storage device in smart premises is considered. The smart grid tied HPS feeds excess power generated in the RES to the utility grid at the time of generation. There is a limitation to feed the HPS power directly to utility grid in view of the energy security and reliability. Also the HPS generation especially from the PV panels is at off peak hours. There is shortage of generation to meet peak demand in power system. One method to address this issue is introduction of time of day tariff. Another method of reducing peak demand is by storage device installed with HPS in smart premises to meet the peak demand and make the demand curve flatten as much as possible. In this chapter, smart grid tied HPS with storage model is developed and optimal system is found out for least energy cost satisfying the required constraints. Smart premises draw power from main grid in peak time only if there is no power generation from HPS and storage. The priority of HPS at off peak and normal hours is to charge the battery to utilise energy at peak hours. The excess power generated by HPS is fed into grid and shortage is met from the grid.

6.2 Structure of Smart Grid Tied Hybrid Power System with Storage

Smart grid tied HPS with storage device is designed to reduce peak consumption of the premises from grid by storing energy generated by the HPS at normal and off peak hours in the storage device and utilised to meet the peak demand. One line diagram of the proposed HPS with power flow of grid is shown in Fig. 6.1 and the configuration of the system is shown in Fig. 6.2. The power from the RES is fed directly to storage battery or utility grid according to the availability of power, SOC of battery and time of use. The load of the premise is met from the grid if there is shortage energy from RES. The grid can accept power from RES or battery and feed the load of the premises at any time. The battery is discharged at peak hours to meet the demand of the premises. The excess energy generated in the premises is fed into grid.

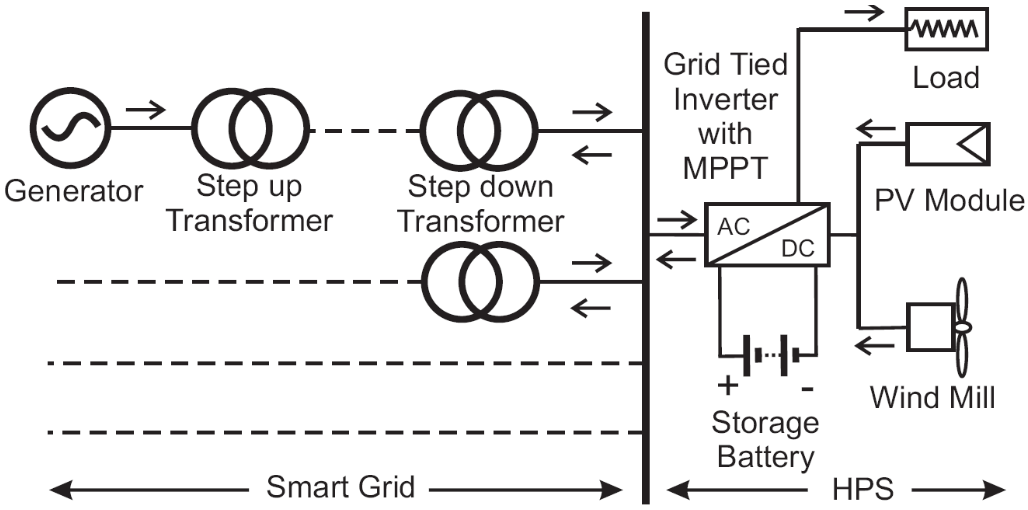


Fig. 6.1 One line diagram of smart grid tied HPS with storage showing power flow of grid

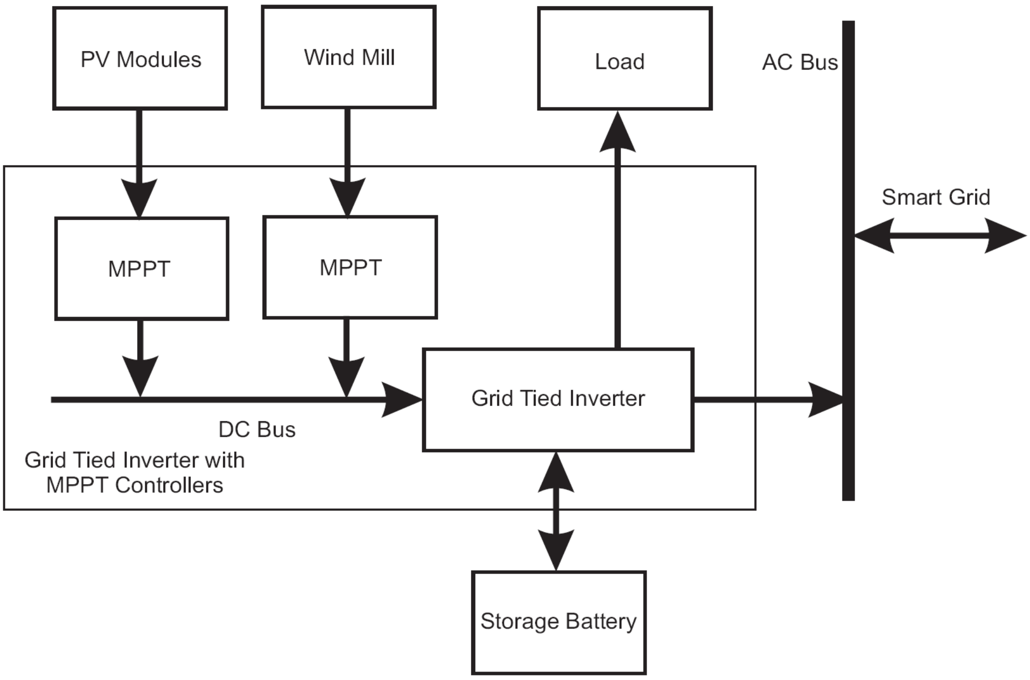


Fig. 6.2 Configuration of smart grid tied HPS with storage

6.3 Mathematical Formulation

In chapter 4 certain rating of the battery is assumed. The value is taken based on the available energy that can be utilised for storing in the storage battery. The available energy is the difference between generation and demand. In this chapter the optimization algorithm is executed to get an optimal capacity for storage battery. This is based on the constraint to ensure minimum reduction in peak demand.

6.3.1 Utility energy cost of smart premises with storage

In smart grid tied system with storage, the storage battery for a combination of RES is determined for minimum energy cost with satisfaction of all constraints. Life time energy cost of utility energy to the smart premises with storage device is determined as equations (4.1) to (4.5). The battery discharge is different for smart premises with storage device in view of conventional grid tied premises. But the format of equation to determine utility energy cost of smart premises with storage device ($C_{\upsilon_{ijk}}$) is same as conventional grid tied premises except the variation of battery rating for a combination of RES are also taken into account as in subsection 6.3.2.

6.3.2 Cost of renewable energy delivered to the smart grid

$C_{\vartheta_{ijk}}$ is the life time cost of RE delivered to the utility grid with PV module rating *i*, wind mill rating *j* and battery rating *k*.

$$C_{\vartheta_{ijk}} = C_{\vartheta m_{ijk}} + C_{\vartheta o_{ijk}} + C_{\vartheta n_{ijk}} \tag{6.1}$$

$$C_{\vartheta m_{ijk}} = \left[\sum_{d=1}^{365} \sum_{t=t_1}^{t_2} \left[| -ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) | - \phi c_{dt_{ijk}} \right] * r_m \right] * \omega \tag{6.2}$$

$$C_{\vartheta o_{ijk}} = \left[\sum_{d=1}^{365} \sum_{t=t_2}^{t_3} \left[| -ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) | - \phi c_{dt_{ijk}} \right] * r_o \right] * \omega \tag{6.3}$$

$$C_{\vartheta n_{ijk}} = \left[\sum_{d=1}^{365} \sum_{t=t_3}^{t_1} \left[| -ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) | - \phi c_{dt_{ijk}} \right] * r_n \right] * \omega \tag{6.4}$$

$C_{\vartheta m_{ijk}}$, $C_{\vartheta o_{ijk}}$ and $C_{\vartheta n_{ijk}}$ are the cost of peak, off peak and normal energy delivered to grid for PV module rating *i*, wind mill rating *j* and battery rating *k*. $\phi c_{dt_{ijk}}$ is the energy to charge the battery at time *t* and day *d* for PV module rating *i*, wind mill rating *j* and battery rating *k*.

6.3.3 Objective function for smart premises with storage

Smart premises HPS with storage device is optimized to determine the most economical rating of HPS satisfying all constraints applicable to the proposed system. The optimal system is found out to minimize the objective function of the system which is expressed as

Minimize

$$C_{\theta_{ijk}} = C_{s_i} + C_{w_j} + C_{v\cong_x} + C_{b_k} + C_{\varpi_{ij}} + C_{\upsilon_{ijk}} - C_{\mu\cong_{ijk}} - C_{\vartheta_{ijk}} \qquad (6.5)$$

Where $C_{\theta_{ijk}}$ is the net energy cost of smart premises with storage for life span of the project with PV module rating i, wind mill rating j and battery rating *k*. $C_{v\cong_x}$ and $C_{\mu\cong_{ijk}}$ are the net investment of inverter with MPPT controllers for smart grid tied system with storage for rating *x* and GEC for the smart premises with storage with PV module rating i, wind mill rating j and battery rating *k*.

6.3.4 Constraints for smart premises with storage

Twelve constraints are to be taken into account for evaluating the proposed system. Maximum RE to grid at off peak hours and normal hours are limited to a value according to the grid capacity and increase the reliability of the grid. It is expressed as

$$E_{o\vartheta_{ijk}} \le \frac{\sum_{d=1}^{365}\sum_{t=t_2}^{t_3} Pl_{dt} * \Lambda}{100} \qquad (6.6)$$

$$E_{n\vartheta_{ijk}} \le \frac{\sum_{d=1}^{365}\sum_{t=t_3}^{t_1} Pl_{dt} * \Lambda}{100} \tag{6.7}$$

Where

$$E_{o\vartheta_{ijk}} = \sum_{d=1}^{365}\sum_{t=t_2}^{t_3} |-\text{ve value of}(Pl_{dt} + \phi c_{dt_{ijk}} - Ps_{dt_i} - Pw_{dt_j})| \tag{6.8}$$

$$E_{n\vartheta_{ijk}} = \sum_{d=1}^{365}\sum_{t=t_3}^{t_1} |-\text{ve value of}(Pl_{dt} + \phi c_{dt_{ijk}} - Ps_{dt_i} - Pw_{dt_j})| \tag{6.9}$$

Excess energy generated at peak hours by the RES is fed into grid in the proposed system and stored energy in the battery is also utilised at peak hours either to meet the demand or to make the load curve of the utility grid flatten. But the peak energy feed into the utility grid is also to be limited to avoid excess penetration to the grid at peak hours for the reliability of the system. This is expressed as

$$E_{\varsigma m_{ijk}} \le El_m \tag{6.10}$$

Where $E_{\varsigma m_{ijk}}$ is the peak energy feed into the grid and El_m is the peak demand of the premise for the life span of the project. These are determined as

$$E_{\varsigma m_{ijk}} = \left[\sum_{d=1}^{365}\sum_{t=t_1}^{t_2} Pl_{dt} - \sum_{d=1}^{365}\sum_{t=t_1}^{t_2} +ve(Pl_{dt} - Ps_{dt_i} - Pw_{dt_j}) + \phi dc_{dtk_{ij}} \right] * \omega \tag{6.11}$$

$$El_m = \left[\sum_{d=1}^{365}\sum_{t=t_1}^{t_2} Pl_{dt} \right] * \omega \tag{6.12}$$

The constraint to ensure minimum RE generation is applied for this system which is expressed as equation (4.7). In smart grid tied system with storage, SOC of the storage battery is limited at both minimum and maximum values as conventional grid tied system. There are two values for minimum SOC, one for peak hours and other for other times of the day as same as conventional grid tied system. The minimum SOC for other times of the day is taken a higher value to store the maximum energy for utilising at peak hours in smart grid tied system with storage. The limitation of SOC for both peak and other times of the day have the same expression as equation (4.9) and (4.10). The average SOC of the battery is to be maintained in a value to ensure the life span of storage battery. This is taken as 7th constraint of this system and explained in subsection 4.3.3, equation (4.11).

The rating of battery variation for a combination of RES is also taken into account in this system. The maximum rating of the battery for each combination of PV module and wind mill is taken as explained in section 4.3.3 for the constant storage battery rating for each combination of PV module and wind mill in conventional grid tied system. This is included as equality constraint for this system. The rating of the battery varies from minimum value to maximum value for a combination of PV module and wind mill which is the 9th constraint. This is expressed as

$$k_{ij\min} \leq k_{ij} \leq k_{ij\max} \tag{6.13}$$

Limit the ratings of PV module and wind mill between minimum and maximum values according to ensure minimum RE generation and lowest rating of each RES to meet the demand of the premises are also taken as inequality constraints for smart grid tied system with storage.

Another constraint to ensure minimum peak demand reduction is applied for smart grid tied system with storage device to determine optimal energy cost and optimal system with required peak demand reduction. This is expressed as

$$E_{\varsigma m_{ijk}} \geq \Upsilon * El_m \tag{6.14}$$

Where Υ is the minimum % of peak demand reduction.

6.4 Simulation

Simulation of the proposed system is carried out as per the flow chart given in Figs. 6.3 and 6.4. Hourly output power of each RES is found out for various combinations of HPS.

Minimum and maximum value of SOC of the battery is fixed to store maximum energy at off peak and normal hours and utilise the stored energy at peak hours to reduce the consumption from the utility grid at peak hours.

Hourly SOC, charge and discharge of the battery are determined as per the flow chart in Fig. 6.4. If Pn_{dt} is less than zero, there is no excess generation in the premises. Then $-Pn_{dt}$ is the shortage of energy in the premises. If SOC of the battery is higher than SOC_{min} the shortage of energy is met from the battery. The battery discharge is ϕdc_{dt} and SOC_{dt} is $SOC_{dt-1} - \phi dc_{dt}/k$. If SOC_{dt} is less than SOC_{min} the battery can discharge only $(SOC_{dt-1}-SOC_{min})*k$. $Pn_{dt}- \phi dc_{dt}$ is drawn from grid and SOC_{dt} is SOC_{min}. If SOC_{dt-1} is less than or equal to SOC_{min}, ϕdc_{dt} is zero and Pn_{dt} is drawn from grid [11], [71], [78].

If Pn_{dt} is greater than zero, the excess energy produced in the premises is utilised to charge battery if the battery in not fully charged.

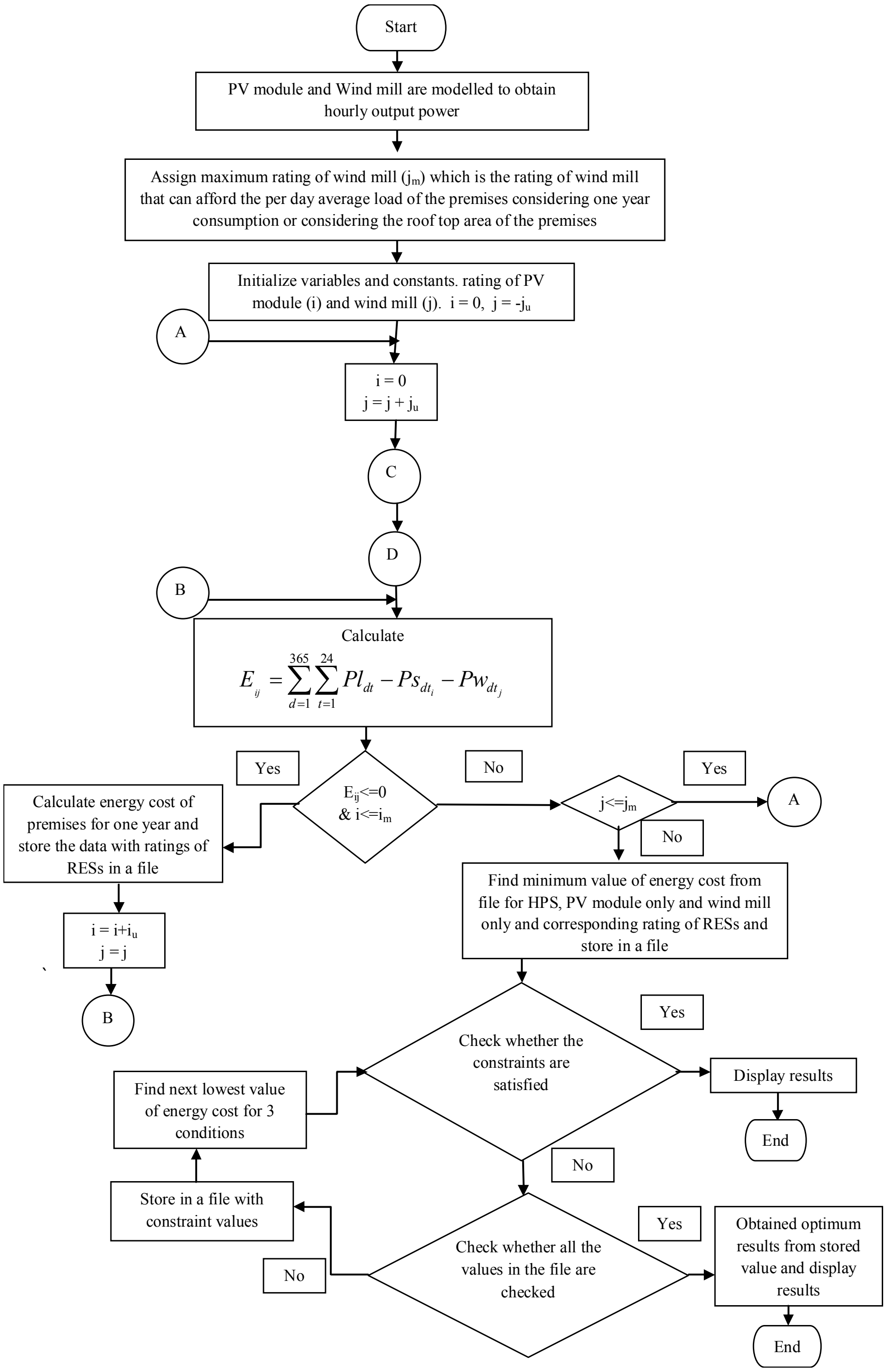


Fig. 6.3 Optimization flow chart of smart grid tied system with storage

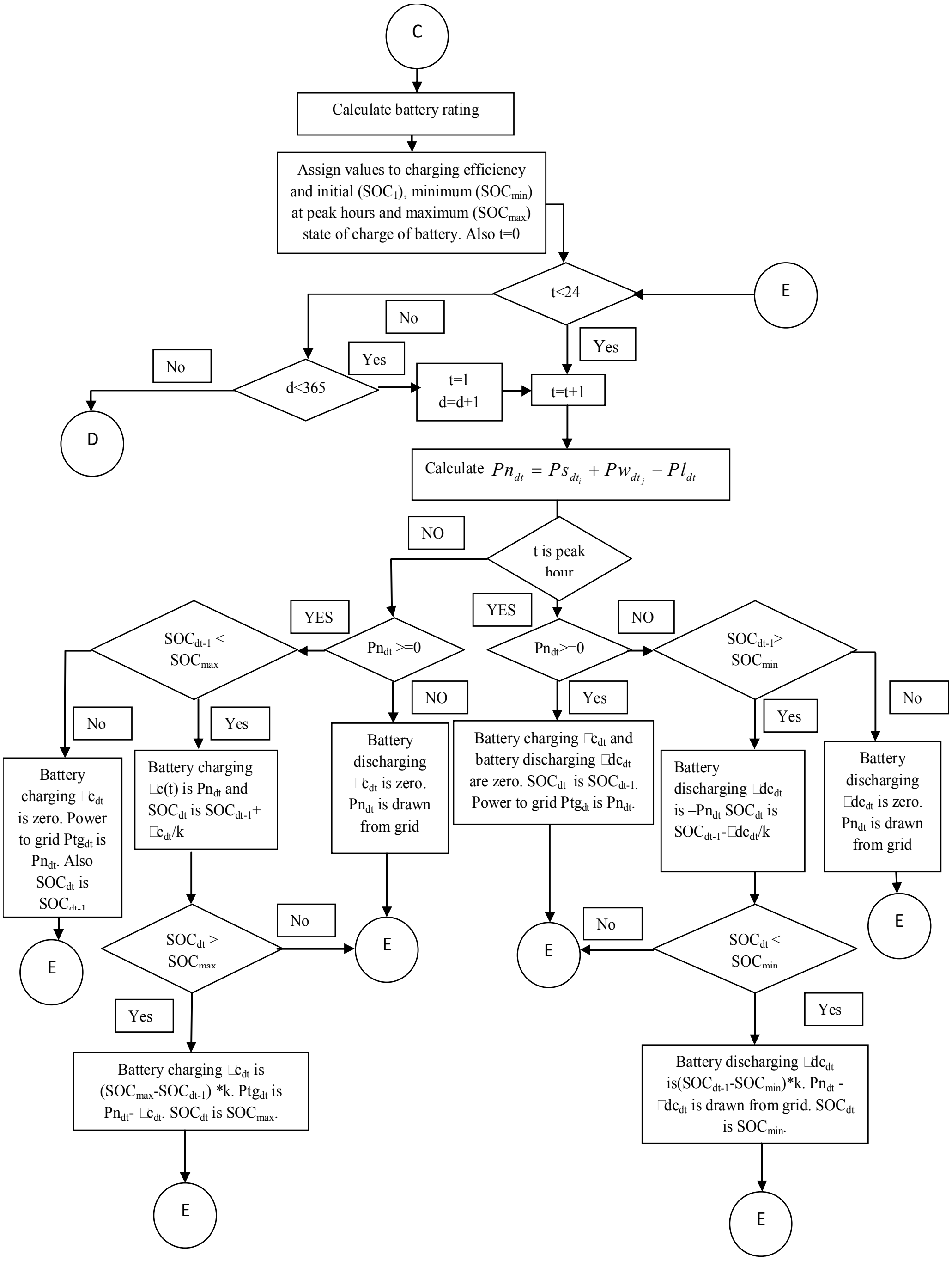


Fig. 6.4 Battery state of charge algorithm of smart grid tied system with storage

Battery charging energy is $Pn_{dt}*\eta_b$ and the SOC_{dt} is $SOC_{dt-1}+\phi c_{dt}/k$. If SOC_{dt} is greater than SOC_{max}, the battery charging energy ϕc_{dt} is $(SOC_{max}-SOC_{dt-1})*k$. $Pn_{dt}-\phi c_{dt}$ is fed into grid and SOC_{dt} is SOC_{max}. If SOC_{dt-1} is equal to SOC_{max}, Pn_{dt} is fed into grid and ϕc_{dt} is zero. If Pn_{dt} is equal to zero, ϕdc_{dt} and ϕc_{dt} are zero and SOC_{dt} is SOC_{dt-1} [11], [71], [78].

The objective function is checked for each combination of HPS and optimal system is found out satisfying all constraints. The values of constants used for the simulation are shown in Table 4.1.

6.5 Analysis

Table 6.1 Optimal rating of HPS and individual RES of smart grid tied system with storage

Particulars	**Unit**	**Load1**			**Load2**		
		HPS	**PV only**	**W only**	**HPS**	**PV only**	**W only**
Location1	kW	PV-0.20 *W-7.00 **B-1.00 ***IC-7.00	PV-7.45 B-8.00 IC-7.00	W-7.00 B-1.00 IC-7.00	PV-0.70 W-2.00 B-1.00 IC-3.00	PV-2.45 B-3.00 IC-2.00	W-2.00 B-1.00 IC-2.00
Location2	kW	PV-3.40 W-6.00 B-1.00 IC-9.00	PV-7.35 B-8.00 IC-7.00	W-6.00 B-1.00 IC-6.00	PV-1.10 W-2.00 B-1.00 IC-3.00	PV-2.45 B-3.00 IC-2.00	W-2.00 B-1.00 IC-2.00
Location3	kW	PV-7.50 W-1.00 B-8.00 IC-9.00	PV-7.50 B-8.00 IC-8.00	W-8.00 B-1.00 IC-8.00	PV-2.50 W-1.00 B-3.00 IC-4.00	PV-2.50 B-3.00 IC-3.00	W-8.00 B-1.00 IC-8.00

*W=Wind mill **B=Battery ***IC=Smart grid tied inverter with MPPT controller

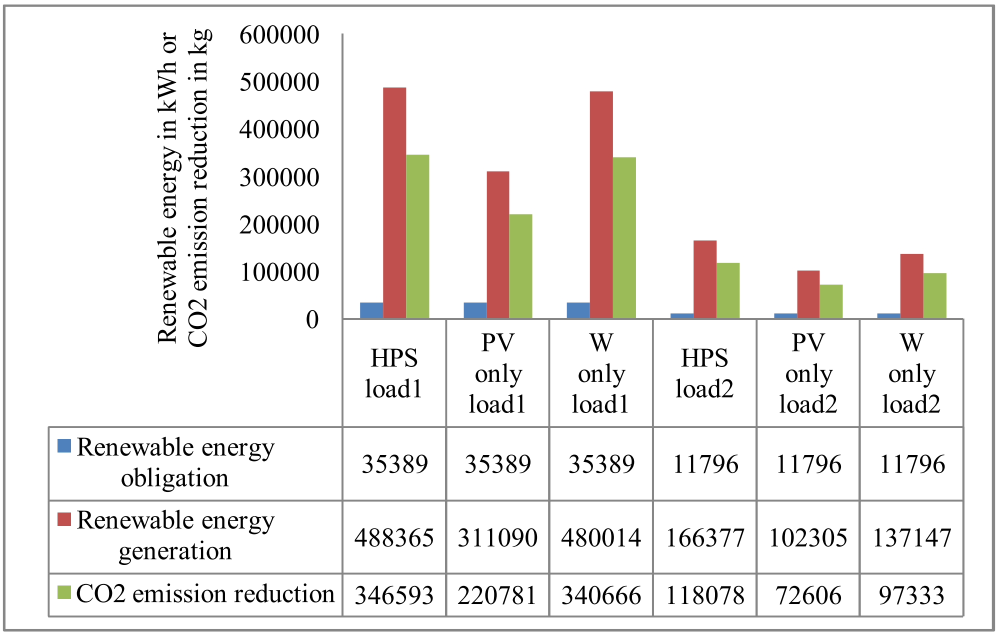
As in chapter 5 this model is also applied at three locations and two different demand profiles. The simulations are carried out for six combinations.

The hourly input data for one year is fed into the developed model and simulation is performed for each location and load. The analysis is also carried out in individual RES also. The optimal configuration of each system is found out and tabulated in Table 6.1 for two loads in three locations.

6.6 Results and Discussion

Having obtained the rating of components of HPS and individual RES for obtaining optimal operation the discussion are carried out on RE generation, SOC of the storage battery, peak demand reduction and optimal energy cost.

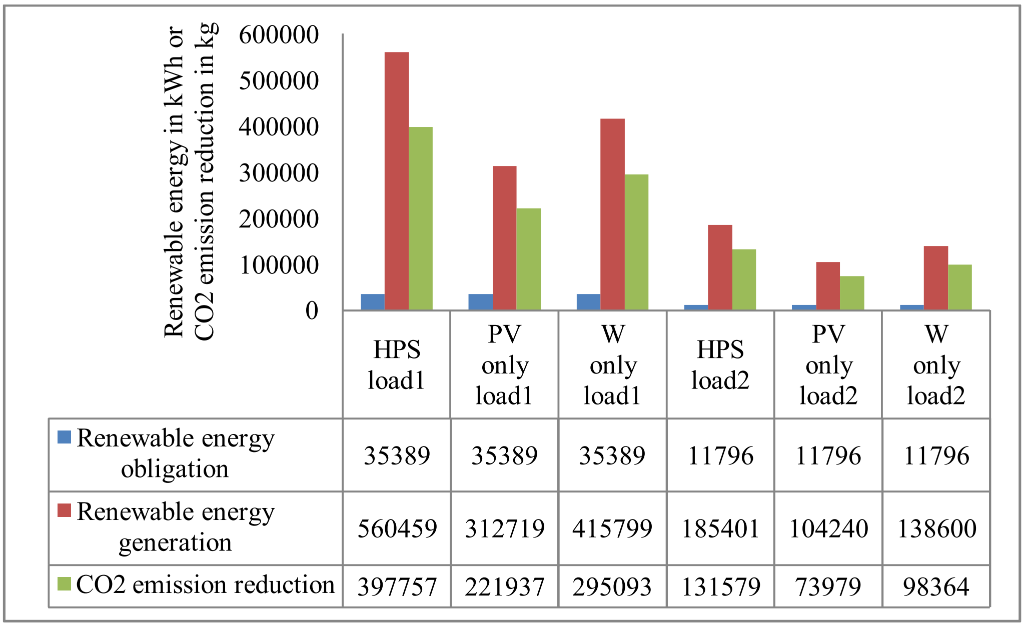
6.6.1 Renewable energy generation



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy generation	488365	311090	480014	166377	102305	137147
🟩 CO2 emission reduction	346593	220781	340666	118078	72606	97333

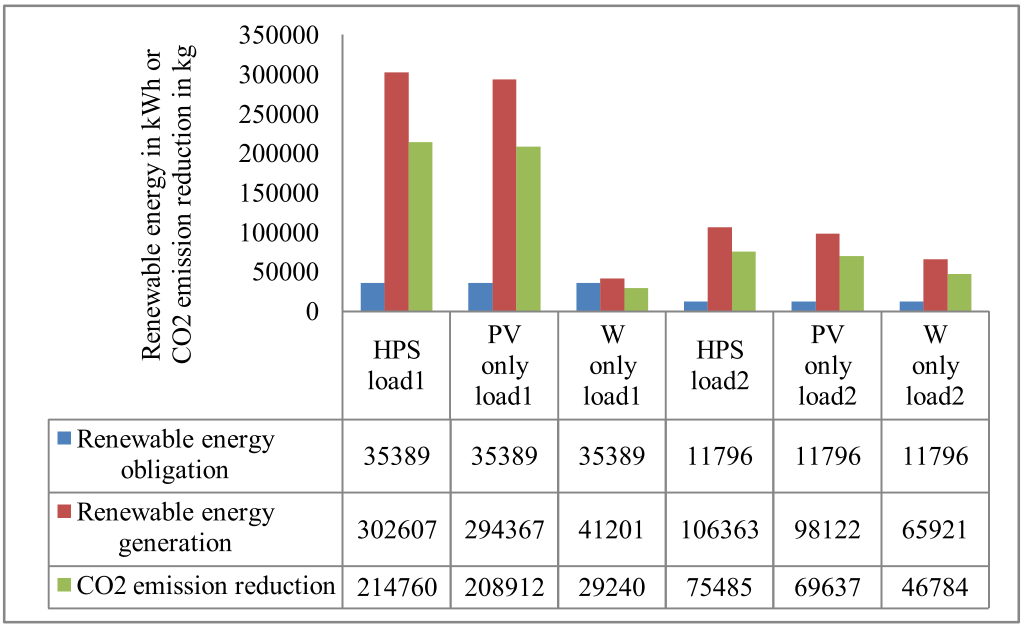
Fig. 6.5 Renewable energy obligation, renewable energy generation and CO_2 emission reduction at location1

Fig. 6.5 shows the RE generation and CO_2 emission reduction with REO for combined and individual RES for load1 and load2 at location1. Fig. 6.6 and Fig. 6.7 show these parameters for location2 and location3 respectively.



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy generation	560459	312719	415799	185401	104240	138600
🟩 CO2 emission reduction	397757	221937	295093	131579	73979	98364

Fig. 6.6 Renewable energy obligation, renewable energy generation and CO_2 emission reduction at location2



	HPS load1	PV only load1	W only load1	HPS load2	PV only load2	W only load2
🟦 Renewable energy obligation	35389	35389	35389	11796	11796	11796
🟥 Renewable energy generation	302607	294367	41201	106363	98122	65921
🟩 CO2 emission reduction	214760	208912	29240	75485	69637	46784

Fig. 6.7 Renewable energy obligation, renewable energy generation and CO_2 emission reduction at location3

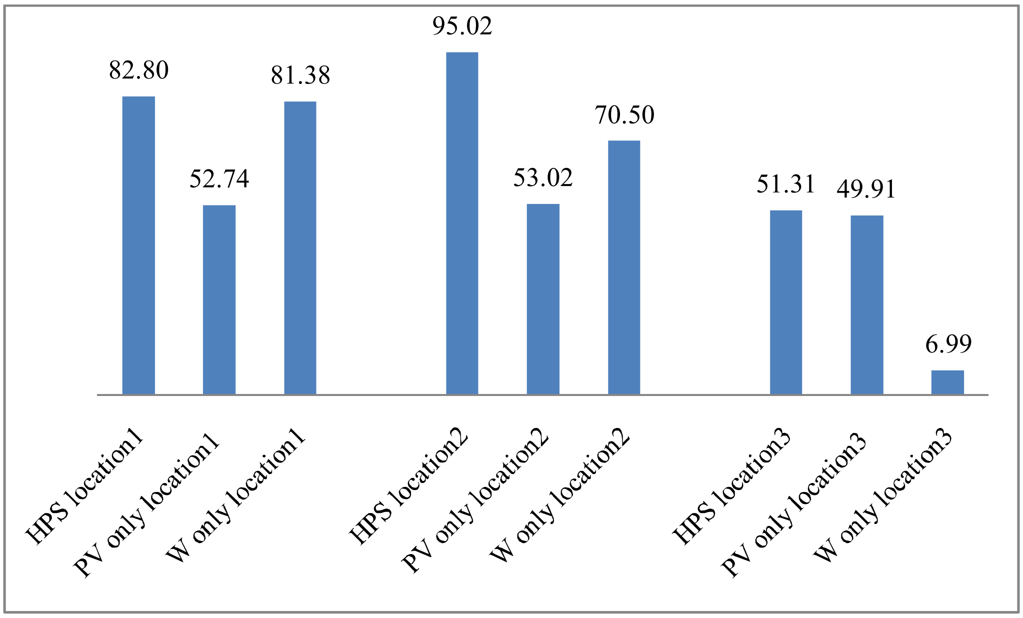


Fig. 6.8 Percentage renewable energy consumption at three locations for load1

The RE generation by the optimal system both combined and individual RES is much higher than the REO of the premises for load1 and load2 in all the locations except for wind mill only system at location3. The percentage of RE consumption with respect to demand of the premises for three locations for individual and combined RES is shown in Figs. 6.8 and 6.9 for load1 and load2 respectively. The RE generation are high for optimal HPS for both loads in all locations compared to PV only and wind mill only condition. At location3, optimal PV only condition also have higher RE generation which is nearer to the value for optimal HPS for both loads. The CO_2 emission reduction is proportional to RE generation. That can also be determined from this study and recorded in Figs. 6.5, 6.6 and 6.7 for three locations with both loads.

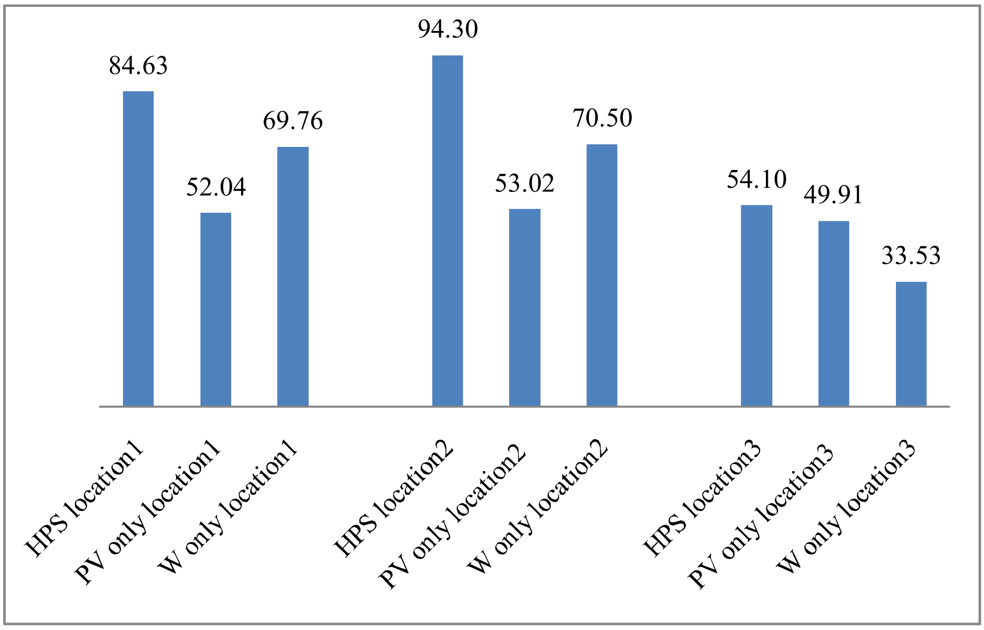


Fig. 6.9 Percentage renewable energy consumption at three locations for load2

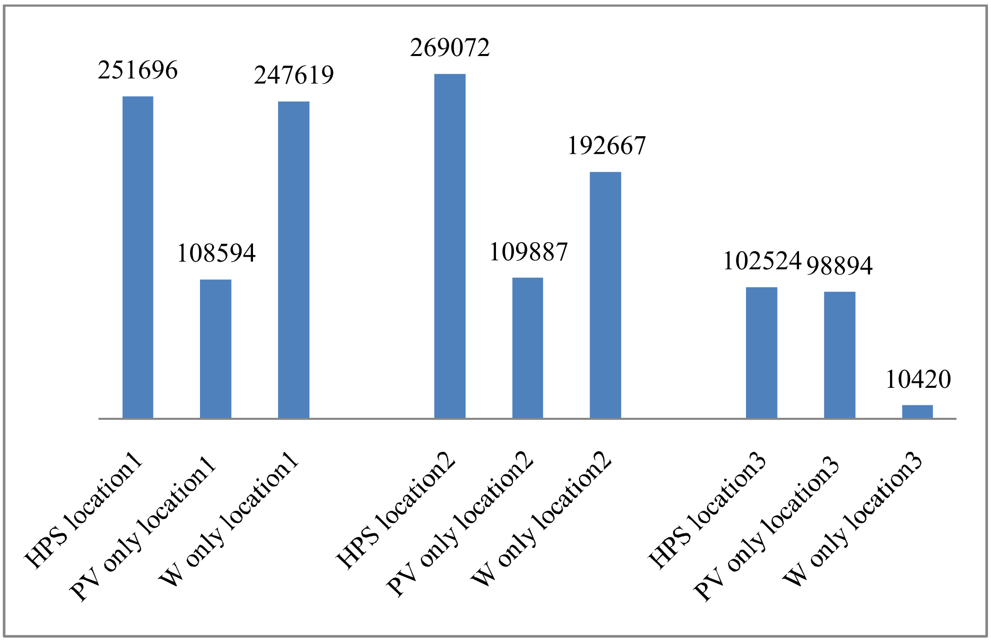


Fig. 6.10 Renewable energy to grid in kWh at three locations for load1

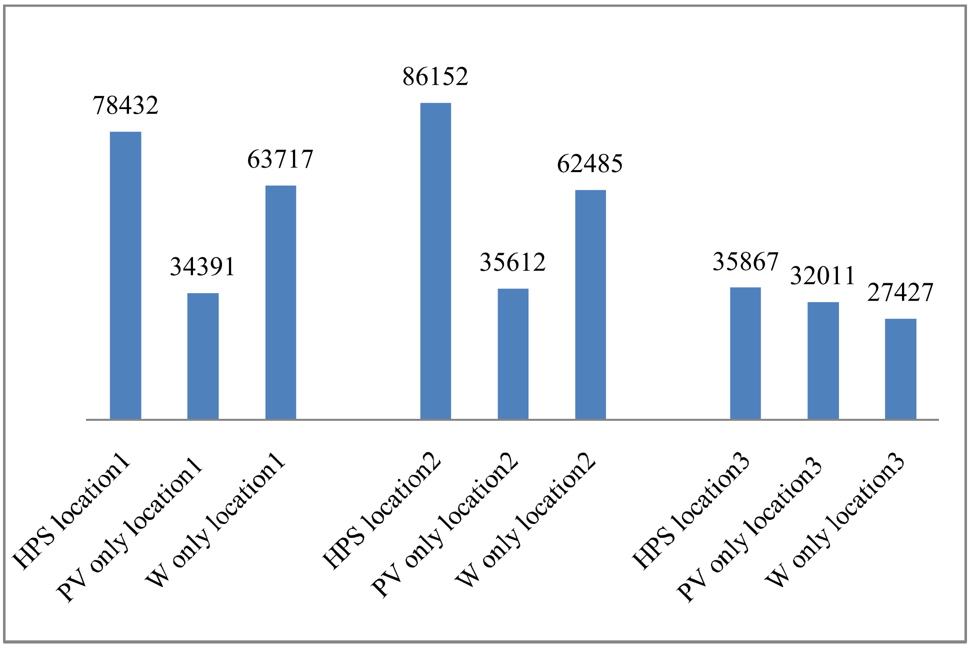


Fig. 6.11 Renewable energy to grid in kWh at three locations for load2

The other factor analysed in this work is the RE to grid. This is to be within limit to ensure the reliability of the grid. The RE to grid is displayed in Figs. 6.10 and 6.11 for load1 and load2 respectively in all three locations for individual and combined RES. It is high for optimal HPS for all locations and loads satisfying the constraint to limit the RE to grid at off peak and normal hours. At location3 PV only optimal system also has high penetration of RE to grid.

6.6.2 State of charge of battery

The SOC of the battery for load1 and load2 in three locations for individual and combined RES are shown in Figs. 6.12 and 6.13 respectively. SOC is high for HPS in all loads and locations. It is more than 71% for location1 and location2. At location3 it is more than 59%. The PV only condition also has SOC nearer to SOC of HPS at location3. In the next sub section describes about peak demand reduction due to RE generation.

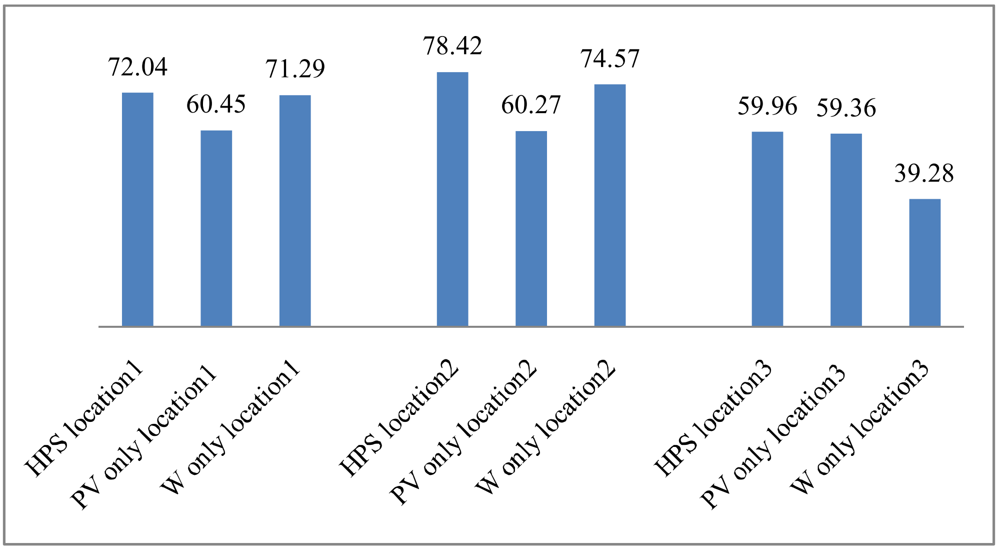


Fig. 6.12 Percentage state of charge of storage battery at three locations for load1

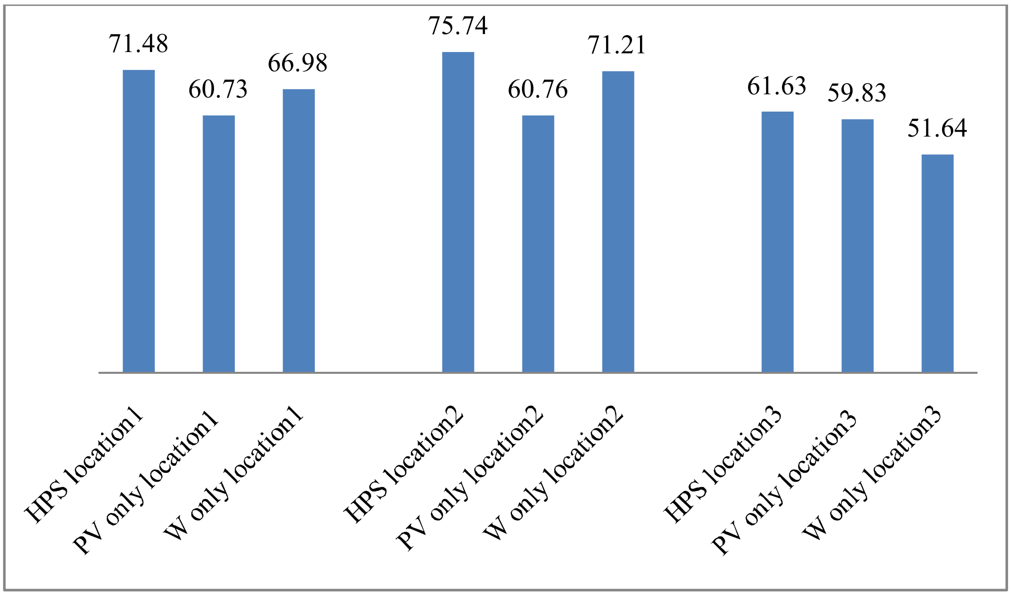
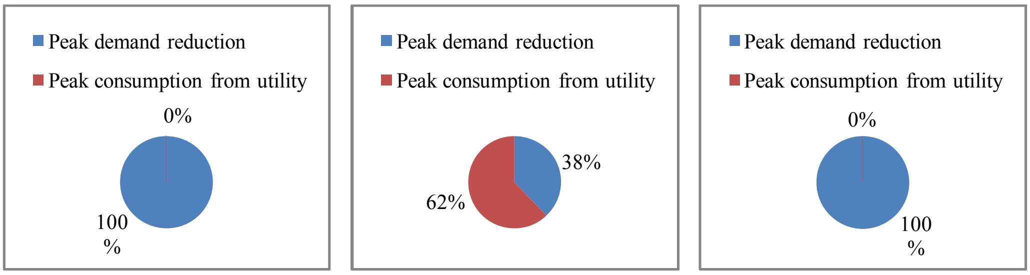


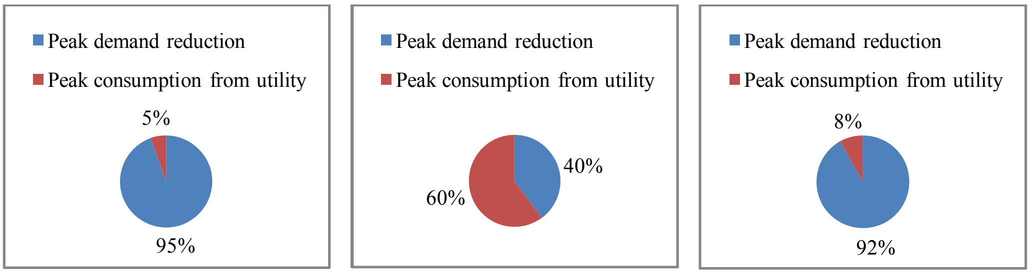
Fig. 6.13 Percentage state of charge of storage battery at three locations for load2

6.6.3 Peak demand reduction

Peak demand reduction and peak consumption from the utility for both loads are displayed in Fig. 6.14, 6.15 and 6.16 for three locations respectively. Peak demand reduction is more than 84% in first two locations for optimal HPS and wind mill only system for both loads and that of PV only system is between 38% to 41% in both loads in these locations. At location3, peak demand reductions are obtained between 37% and 46% except for wind mill only system for load1. Optimal HPS has high peak demand reduction compared to other configurations at location3. Even though PV only optimal system has less peak demand reduction in all locations compared to HPS, it has peak demand reduction near to HPS at location3.

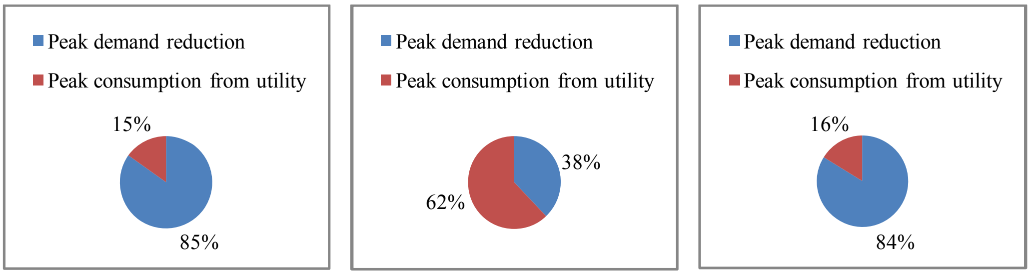


(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1

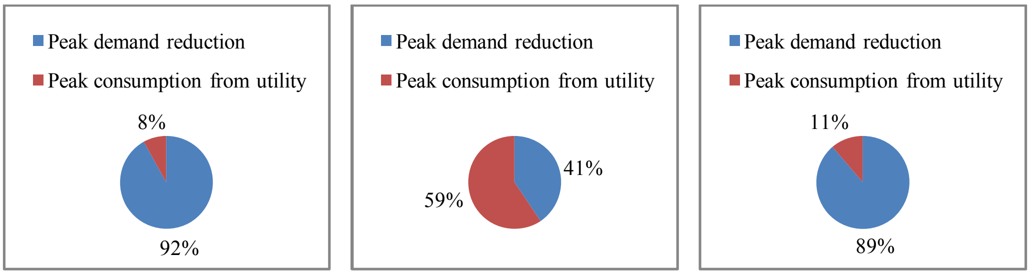


(a) HPS for load2 (b) PV only for load2 (c) Wind mill only for load2

Fig. 6.14 Peak demand reduction of premises at location1 for both loads

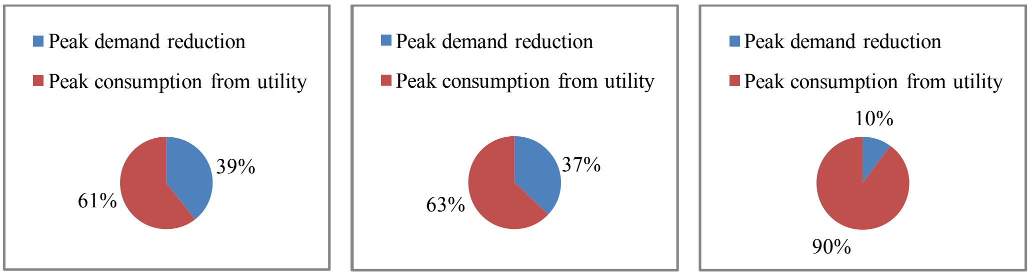


(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1

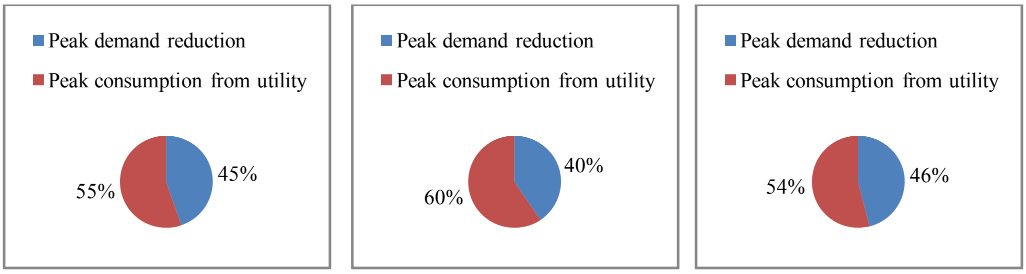


(a) HPS for load2 (b) PV only for load2 (c) Wind mill only for load2

Fig. 6.15 Peak demand reduction of premises at location2 for both loads



(a) HPS for load1 (b) PV only for load1 (c) Wind mill only for load1

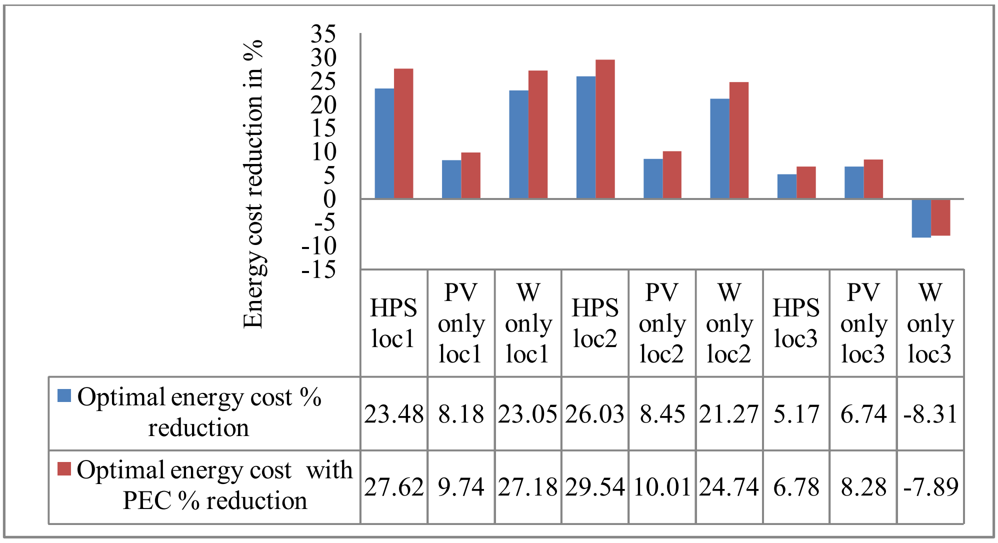


(a) HPS for load2 (b) PV only for load2 (c) Wind mill only for load2

Fig. 6.16 Peak demand reduction of premises at location 3 for both loads

The life time energy cost of the optimal system is determined in this algorithm to compare it with conventional energy cost. Comparison of combined and individual RES optimal systems is also carried out in terms of life time energy cost to determine most financially feasible system. This is discussed in the next subsection.

6.6.4 Optimal energy cost of smart grid tied system with storage

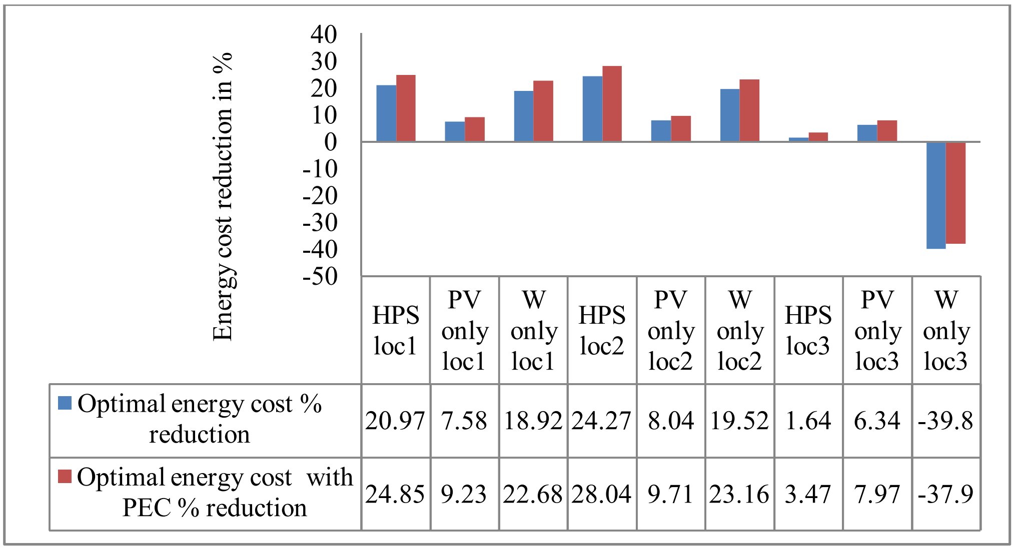


	HPS loc1	PV only loc1	W only loc1	HPS loc2	PV only loc2	W only loc2	HPS loc3	PV only loc3	W only loc3
🟦 Optimal energy cost % reduction	23.48	8.18	23.05	26.03	8.45	21.27	5.17	6.74	-8.31
🟥 Optimal energy cost with PEC % reduction	27.62	9.74	27.18	29.54	10.01	24.74	6.78	8.28	-7.89

Fig. 6.17 Comparison of optimal energy cost with conventional energy cost at three locations for load1

The Fig. 6.17 and Fig. 6.18 show the comparison of optimal life time energy cost of combined and individual RES system with conventional energy cost at location1, location2 and location3 for load1 and load2 respectively. The optimal energy cost with PEC is also taken into account in the comparison.

The optimal ratings of HPS for load1 are 0.20 kW PV, 7kW wind mill, 1kW storage battery and 7kW inverter with MPPT controller as tabulated in Table 6.1. The optimal HPS for load2 is 0.7kW PV module, 2kW wind mill, 1kW storage battery and 3kW inverter with MPPT controllers. The optimal energy cost for life span of project is less for HPS at location1 for both loads. The optimal energy costs for load1 and load2 at location1 are INR 83.19lakh and INR 28.88lakh respectively which are about 23% and 21% less than conventional energy cost.



	HPS loc1	PV only loc1	W only loc1	HPS loc2	PV only loc2	W only loc2	HPS loc3	PV only loc3	W only loc3
🟦 Optimal energy cost % reduction	20.97	7.58	18.92	24.27	8.04	19.52	1.64	6.34	-39.8
🟥 Optimal energy cost with PEC % reduction	24.85	9.23	22.68	28.04	9.71	23.16	3.47	7.97	-37.9

Fig. 6.18 Comparison of optimal energy cost with conventional energy cost at three locations for load2

The Optimal HPS for load 1 at location2 is 3.4kW PV module, 6kW wind mill, 1kW storage battery and 9kW inverter with MPPT controllers. That for load2 is 1.1kW PV module, 2kW wind mill, 1kW storage battery and 3kW inverter with MPPT controllers. The optimal life time energy costs for load1 and load2 are INR80.42lakh and INR27.67lakh respectively. The optimal life time energy costs are about 26% and 24% less than conventional energy cost at location2 for load 1 and load 2 respectively.

Least optimal energy cost at location3 for both loads is obtained for PV module only system. So PV module system is suitable for location3. The optimal rating for load1 is 7.5kW PV module, 8kW storage battery and 8kW inverter with MPPT controllers and for load2 is 2.5kW PV module, 3kW storage battery and 3kW inverter with MPPT controllers. The optimal energy costs for load1 and load2 are INR 101.39lakh and INR 34.22lakh respectively which are about 6% less than conventional energy cost.

The optimal life time energy cost with PEC is less for optimal HPS for locations1 and location2 and which is less for PV only system at location3 as same as optimal life time energy cost. In all 6 cases the optimal energy cost is less than conventional energy cost. So RES are financially viable in a building if smart grid tied systems with storage battery are provided.

It is summarised that smart grid tied HPS with storage battery leading to minimum energy cost for each premises at high wind locations and PV only system at low wind location. RE consumption is high for high wind locations which are more than 82% with respect to demand of the premises compared to nearer 50% at low wind location. So the same reductions in CO_2 emission are also observed in each location. RE to grid is high for optimal HPS for all locations and loads satisfying the constraint to limit the RE to grid at off peak and normal hours. In low wind location, PV only optimal system also has high penetration of RE to grid. SOC of the storage battery is high at high wind locations which is more than 71% compared to nearer 59% at low wind location. The peak demand reduction is also high at high wind locations which are more than 85%. That of low wind location is obtained between 37% and 40%. Optimal HPS of smart grid tied HPS with storage is economically viable with about 21% to 26% life time energy cost reduction at high wind location and about 6% cost reduction at low wind location. In the next section, the sensitivity analysis is carried out for the optimal system.

6.7 Sensitivity Analysis

As discussed in section 4.7 and 5.7 the sensitivity analysis is done at location1 for both loads to analyse the effect of variation in conventional energy cost and investment of HPS components assumed for simulation.

6.7.1 Changes in the cost of energy drawn from grid

As same as the previous sensitivity analysis in chapter 4 and 5, a change of 10% decrease and increase in proposed conventional energy cost is considered for sensitivity analysis in cost of energy drawn from grid.

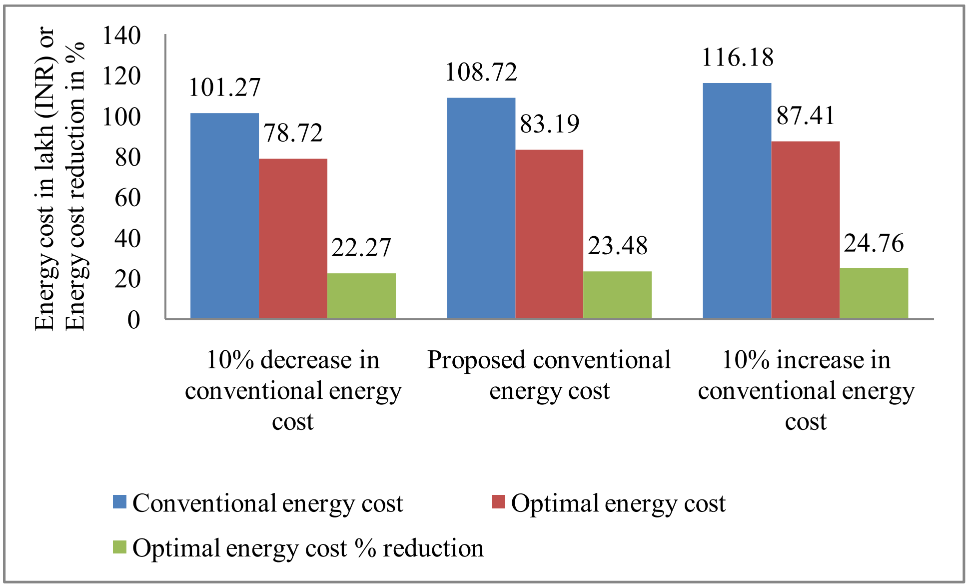


Fig. 6.19 Sensitivity analysis on cost of energy drawn from grid at location1 for load1

From sensitivity analysis it is observed even under a 10% reduction in the conventional energy cost, the HPS is more economical and optimal energy cost is INR 78.72lakh for load1 at location1 and INR 27.51lakh for load2 at the same location as shown Figs. 6.19 and 6.20 respectively. The optimal energy cost is increasing with conventional energy cost but the % reduction of optimal energy cost with respect to conventional energy cost is high. So increase in conventional energy cost makes the HPS more financially feasible.

6.7.2 Change in the cost of HPS components

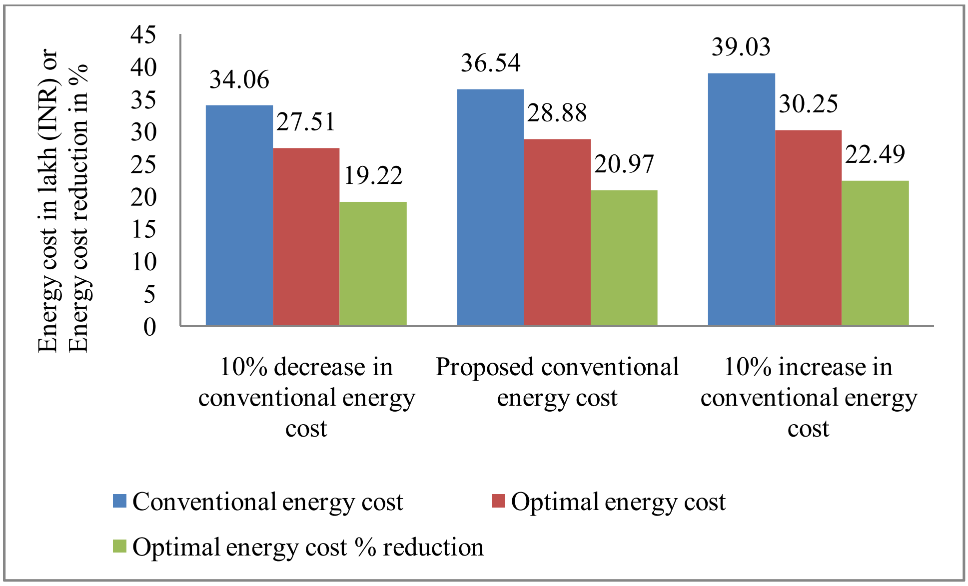


Fig. 6.20 Sensitivity analysis on cost of energy drawn from grid at location1 for load2

The cost of HPS components PV module, wind mill and inverter with MPPT controllers may change possibly down wards. Even though, effect of component variation on optimal energy cost is analysed by taking 10% decrease and increase in the cost of component. The results indicate that the optimal energy cost is increasing with increase in cost of HPS components. But the optimal energy cost for 10% increase in component of HPS is less than conventional energy cost for both loads as displayed in Fig. 6.21 and Fig. 6.22. The decrease in cost of HPS components which we expected in future, reduce the optimal energy cost for both loads and makes the system more commercially viable.

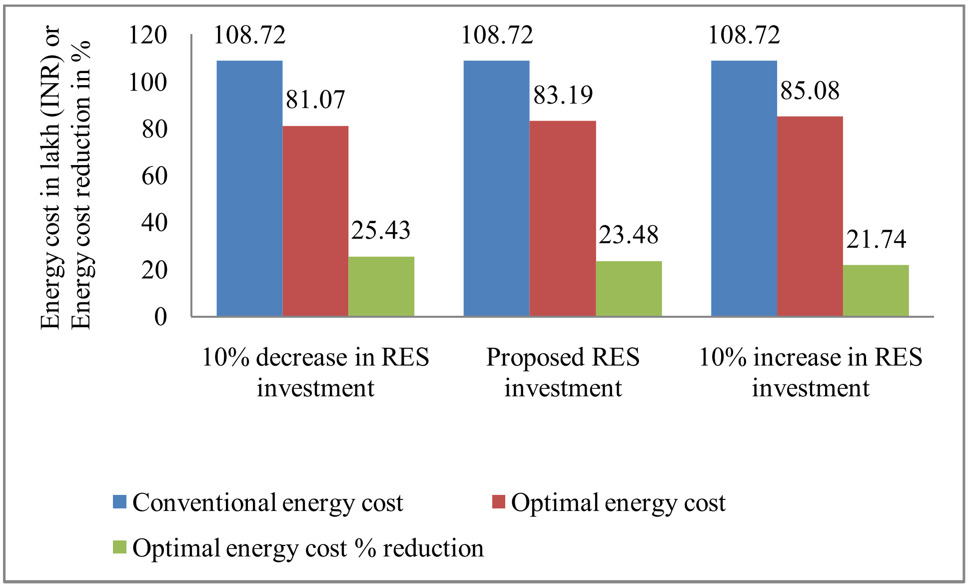


Fig. 6.21 Sensitivity analysis on component of HPS investment at location1 for load1

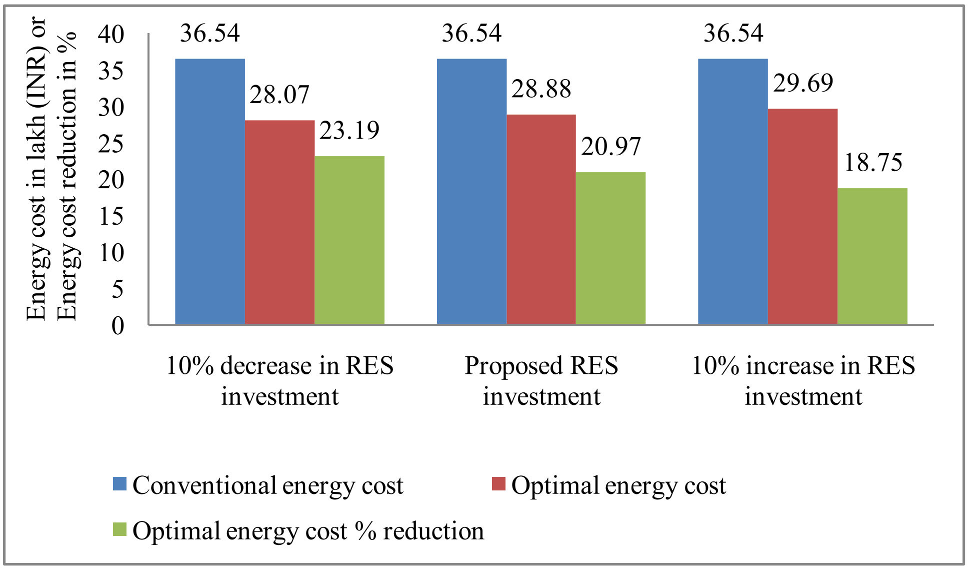


Fig. 6.22 Sensitivity analysis on component of HPS investment at location1 for load2

The optimal energy cost is very much less than conventional energy cost for all cases. So RES are viable for all locations and loads. Optimal HPS can be determined if we know the availability of resources for RES and demand of the premises. The energy cost of the premises can be reduced by selecting optimal HPS.

6.7 Conclusion

This chapter deals with the development of mathematical model and optimization algorithm to find out optimal RE system with storage for smart premises leading to minimum life time energy cost in the premises and satisfying the constraints appropriate for the system. This model is applied on three different locations and two demand patterns in each location. The locations are selected based on environmental condition and demand profile is selected to analyse the impact of high and low demand at each location. Least energy cost with optimal rating of HPS for smart grid tied system with storage device which satisfying the constraints are found out using the developed algorithm.

It is likely that the cost of energy drawn from grid and cost of components of HPS may vary even the value is determined in view of future variation. To find the effect of the change both up and down, sensitivity analysis is also carried out to examine whether the optimization is still valid. It is observed that there is saving in energy cost in all locations of both demand curves and optimal system is same.

Chapter 7

Comparison of Configurations

7.1 Introduction

The work investigated whether it is possible to find an economic alternative for drawing energy from the utilities, over long period of time by getting power from RES installed on roof top of the premises. The RES considered are PV system and wind mill which are widely available. Availability of solar and wind power vary from place to place. Hence sample of three locations are considered for the study. Two locations are selected with abundant wind power and the third location is with moderate wind power. Solar power availability in these three locations is in normal range but each hour solar power is different in each location according to climate condition. In all the location the utility grid is available. The work carried out to determine optimal system either one or both RES are available in the location. For the given load curve of the premises it may be possible to deliver excess energy generated in the premises to the grid by which a part of the cost of RE generation can be recovered from the utilities. Some time utility may not permit the RE to be pumped to the grid even if there is excess generation. It is also possible to install storage battery in the premises to store excess energy and use it to meet the demand of the premises when required or pump energy to grid when storage battery is fully charged or if storage battery is not installed to store energy, the surplus energy available from RES is fed into grid at the time of generation. Considering all these HPS is configured in three ways based on energy flow and storage facility.

1. Utility grid will not accept energy but storage facility is provided (Conventional grid tied system)
2. Utility will accept energy and deliver energy as needed but no storage battery provided in the premises (Smart grid tied system)
3. Utility will accept and deliver energy from RES with storage battery which can cause flattening of load curve (Smart grid tied system with storage)

Models for these three configurations were developed in chapters 4, 5 and 6 respectively. Developed algorithms were applied to obtain optimal systems with least energy cost satisfying constraints appropriate for each configuration. This model is applied in three different site conditions with two demand profiles. Algorithm is also applied for individual RES. The results were compared. In this chapter optimal systems of these three configurations are compared to determine which one is more suitable for a location and load.

7.2 Data for Comparison

Optimal systems of each configuration are compared in terms of RE generation, CO_2 emission reduction, RE to grid, average SOC, peak demand reduction and life time energy cost. RE generation and CO_2 emission reduction are the factors to analyse environmental impact of the system.

RE transfer to grid is to be limited to ensure the power system stability and reliability. The RE is fed into smart grid in second and third configuration. In the first configuration there is no transmission of energy to grid. The excess energy generated in RES may be loss as dump load. It is to be reduced to obtain better performance of the system.

The next factor analysed in this work is average SOC of the battery is one of the main factors to determine life cycle of the battery. The life cycle of the battery is increased by increasing average SOC. But it affects the capacity utilisation of battery to store RE and the availability of stored energy for peak load reduction. Average SOC is to be optimized to ensure the life span and capacity utilisation of storage device.

The storage device in first and third configurations helps to reduce peak demand and to strengthen the grid. The most suitable system for peak demand reduction is identified by verifying the peak demand reduction of optimal system for each configuration.

Reduction in life time energy cost is the optimization objective of the work. The optimal system with least life time energy cost is identified to determine the most suitable system in a particular location and demand profile. Life time energy cost with PEC is also determined in this work to analyse the impact of PEC in the optimal life time energy cost for each configuration.

7.3 Comparison

Location1 and location2 are high wind locations and location3 is low wind location. At location1 and location2 the optimal system is HPS where as PV module is more suitable for location3 for all three configurations. Optimal systems of each configuration for three locations are displayed in Table 7.1.

Table 7.1 Optimal systems for three configurations

Particulars	**Unit**	**Load1**			**Load 2**		
		Conventional grid tied system	Smart grid tied system	Smart grid tied system with storage	Conventional grid tied system	Grid tied system	Grid tied system with storage
Location1	kW	PV-2.35 *W-3.00 **B-16.00 ***IC-5.00	PV-1.10 W-7.00 IC-8.00	PV-0.20 W-7.00 B-1.00 IC-7.00	PV-1.10 W-1.00 B-6.00 IC-2.00	PV-0.70 W-2.00 IC-3.00	PV-0.70 W-2.00 B-1.00 IC-3.00
Location2	kW	PV-2.30 W-3.00 B-15.00 IC-5.00	PV-3.40 W-6.00 IC-9.00	PV-3.40 W-6.00 B-1.00 IC-9.00	PV-1.20 W-1.00 B-6.00 IC-2.00	PV-1.10 W-2.00 IC-3.00	PV-1.10 W-2.00 B-1.00 IC-3.00
Location3	kW	PV-6.80 B-16.00 IC-7.00	PV-7.90 IC-8.00	PV-7.50 B-8.00 IC-8.00	PV-2.25 B-5.00 IC-2.00	PV-2.50 IC-3.00	PV-2.50 B-3.00 IC-3.00

*W=Wind mill   **B=Battery   ***IC=Grid tied inverter with MPPT controller

7.3.1 Renewable energy generation and CO_2 emission reduction

The RE generation and CO_2 emission reduction are the factors to analyse the environmental impact of the HPS. RE energy generation is high for smart grid tied HPS for both loads in all three locations as shown in Fig. 7.1 and Fig. 7.2. CO_2 emission reduction is also high for this system since it is proportional to RE generation.

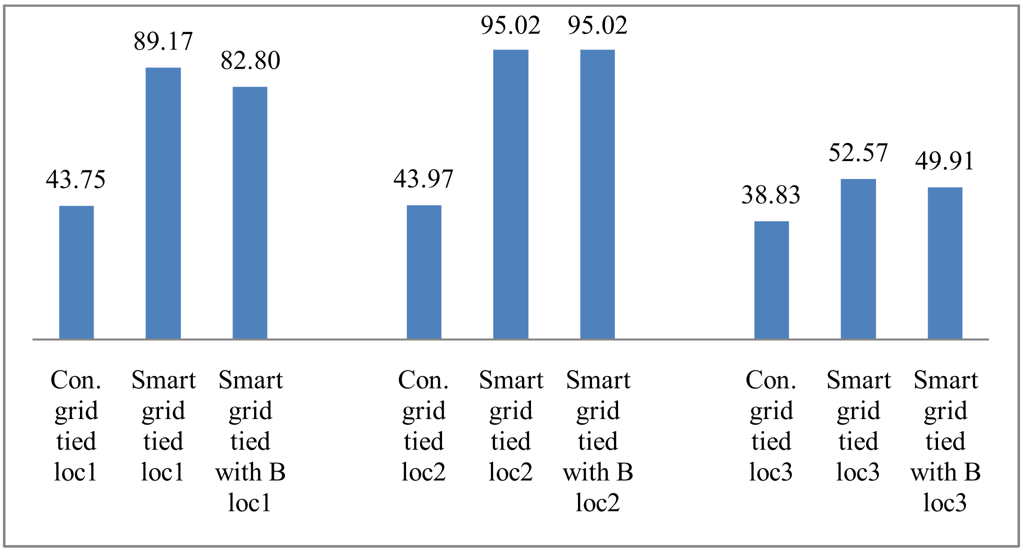


Fig. 7.1 Percentage renewable energy consumption for three configurations at three locations for load1

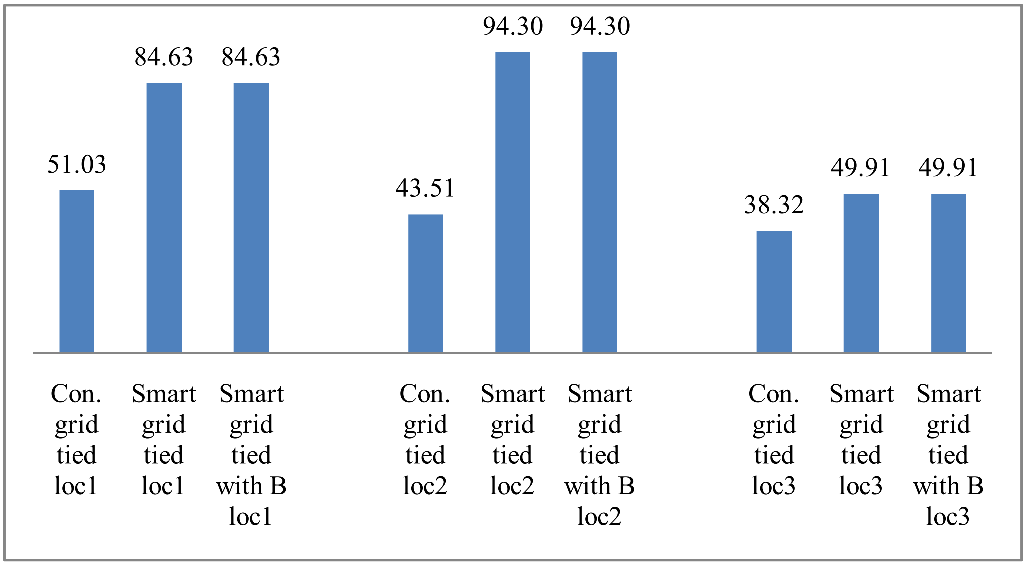


Fig. 7.2 Percentage renewable energy consumption for three configurations at three locations for load2

In some conditions these are as same as smart grid tied system for smart grid tied system with storage and for other conditions which are near to the value of smart grid tied system. Bi-directional smart grid tied systems with or without storage is recommended as optimal systems in all locations in view of environmental impact.

7.3.2 Renewable energy to grid

The grid is to be strengthened and protection and custom power devices are to be provided in the grid to feed RE generated into the grid. The investment for the mitigating devices will increase with the increase in RE penetration to improve power quality of unbalanced power system. The RE can be fed to grid only for smart grid tied system and smart grid tied system with storage device only. These two configurations are compared in this section. RE to grid for the optimal systems for these configurations in three locations for load1 and load2 are plotted in Fig. 7.3 and 7.4 respectively.

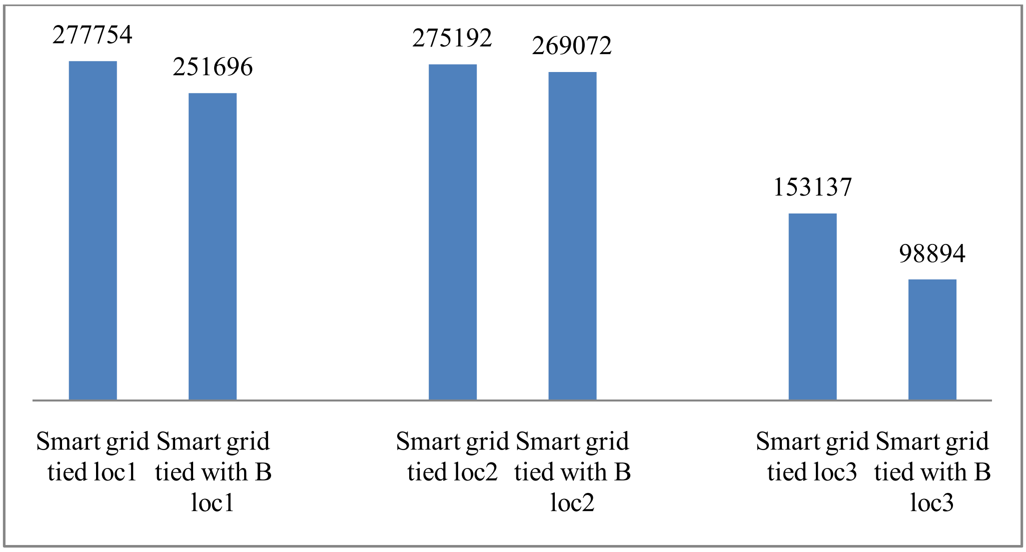


Fig. 7.3 Renewable energy to grid in kWh for two configurations at three locations for load1

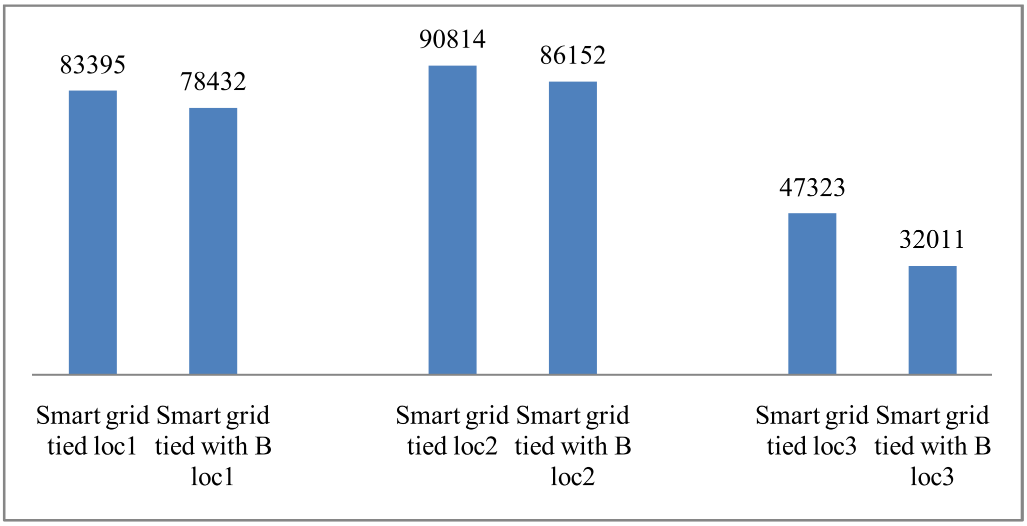


Fig. 7.4 Renewable energy to grid in kWh for two configurations at three locations for load2

This study shows that smart grid tied HPS with storage reduces RE to grid for the same generation of RE which improves the stability and reliability of power system compared to smart grid tied HPS.

7.3.3 State of charge of storage battery

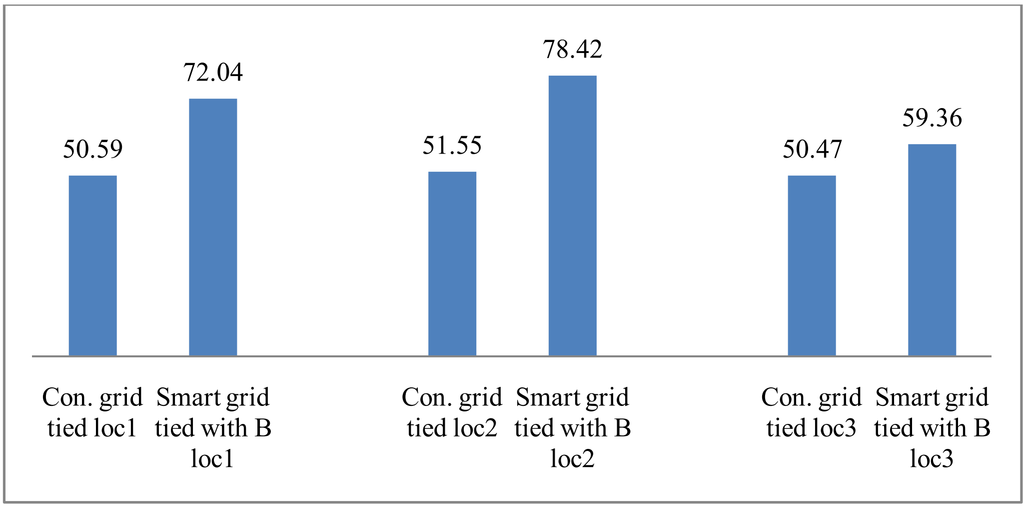


Fig 7.5 Percentage average state of charge of storage battery for two configurations at three locations for load1

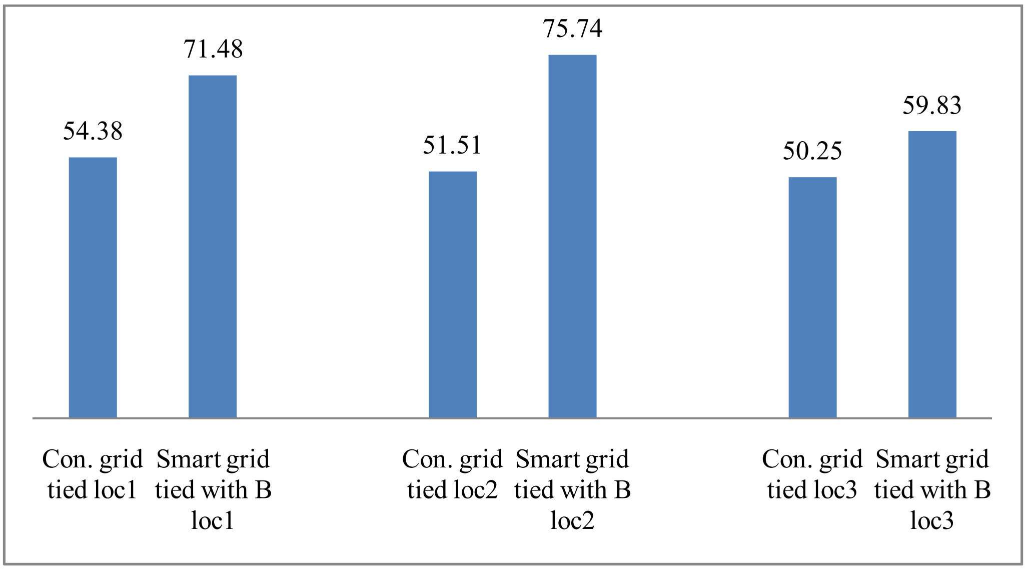
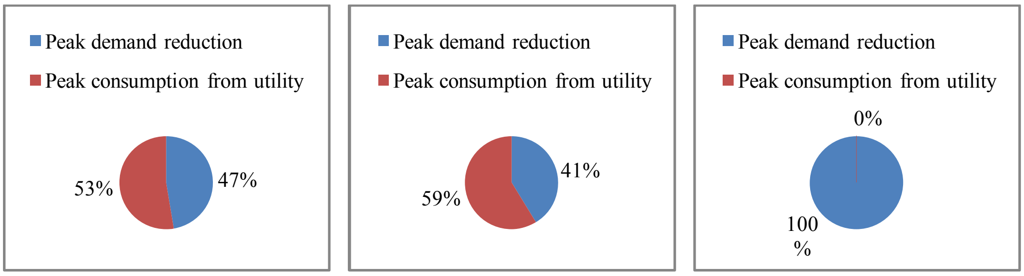


Fig 7.6 Percentage average state of charge of storage battery for two configurations at three locations for load2

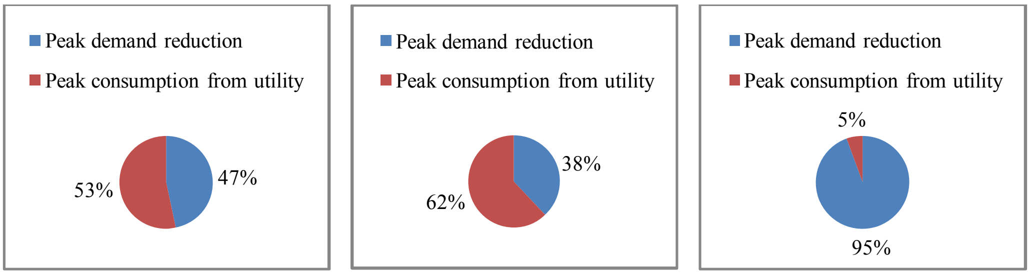
There is no storage device in smart grid tied system. So there is no question about SOC. But in conventional grid tied system and smart grid tied system with storage, the average SOC of storage battery should be higher than 50% to ensure the life span of the storage device. The life cycle of lead acid battery is increased with increase in average SOC.

Average SOC for two configurations and three locations for load1 and load2 are shown in Fig. 7.5 and Fig. 7.6 respectively. Average SOC is higher for smart grid tied HPS with storage for both load1 and load2 with respect to conventional grid tied system which is greater than 71% in first two locations and 59% for location3. This ensures higher life time for storage devices in smart grid tied HPS with storage. The average SOC is low for location3 which reduce the life cycle of storage device at location3 compared to location1 and location2.

7.3.4 Peak demand reduction

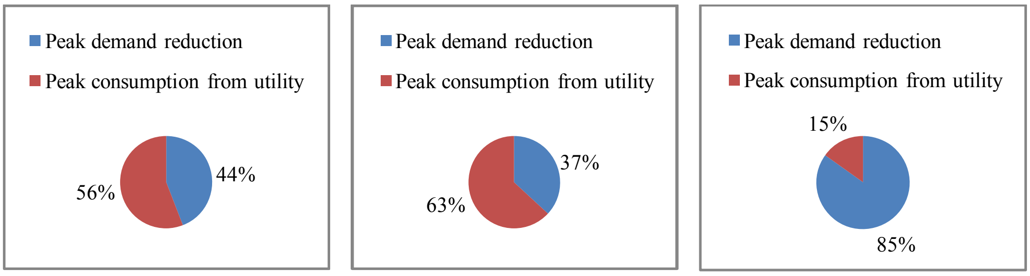


(a) Conventional grid tied system (load1) (b) Smart grid tied system (load1) (c) Smart grid tied system with B (load1)

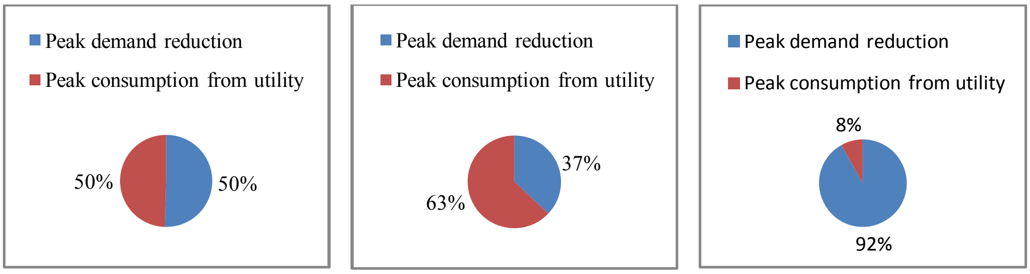


(d) Conventional grid tied system (load2) (e) Smart grid tied system (load2) (f) Smart grid tied system with B (load2)

Fig. 7.7 Peak demand reduction of the optimal systems for three configurations and both loads at location1

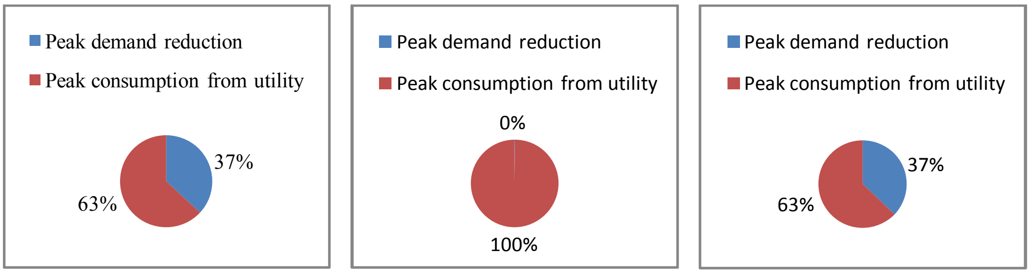


(a) Conventional grid tied system (load1)(b) Smart grid tied system (load1)(c) Smart grid tied system with B (load1)

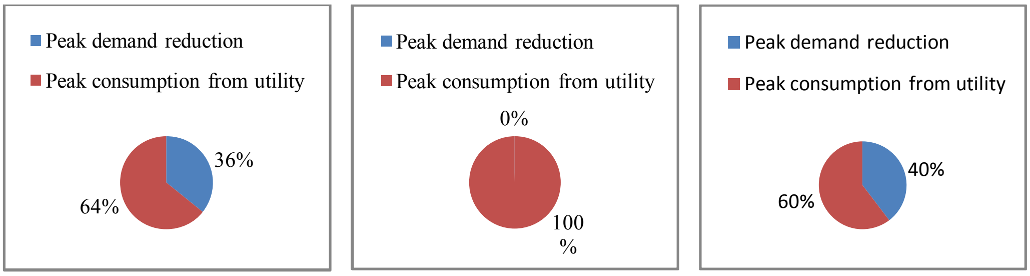


(d) Conventional grid tied system (load2)(e) Smart grid tied system (load2) (f) Smart grid tied system with B (load2)

Fig. 7.8 Peak demand reduction of the optimal systems for three configurations and both loads at location2



(a) Conventional grid tied system (load1) (b) Smart grid tied system (load1) (c) Smart grid tied system with B (load1)



(d) Conventional grid tied system (load2) (e) Smart grid tied system (load2) (f) Smart grid tied system with B (load2)

Fig. 7.9 Peak demand reduction of the optimal systems for three configurations and both loads at location3

Peak demand of the premises is split into peak demand reduction and peak consumption from utility for all three configuration and both loads and plotted in Fig. 7.7, Fig. 7.8 and Fig. 7.9 for three locations. Peak demand reduction is high for smart grid tied system with storage device for all three locations. More than 85% peak demand reduction can be achieved at location1 and location2. Peak demand reduction of 37% and 40% is obtained for smart grid tied system with storage for location3 for load1 and load2 compared to 0% for smart grid tied system.

7.3.5 Life time energy cost

Optimal energy cost for three configurations in three locations for load1 and load2 are plotted in Fig. 7.10 and Fig. 7.11. These are all less than conventional energy cost except at location3 for load1 for conventional grid tied system. So energy cost can be reduced by providing optimal RE systems for any of the configuration discussed in this work in most of the locations and loads. The optimal energy cost with PEC is plotted for all three configurations in three locations for both loads in Fig. 7.10 and Fig. 7.11. This is less than conventional energy cost for all these configurations. So PEC is provided in some location to make conventional grid tied system financially feasible. Smart grid tied system has less optimal energy cost for both loads in all three locations with or without PEC which is the most suitable system in view of commercial viability.

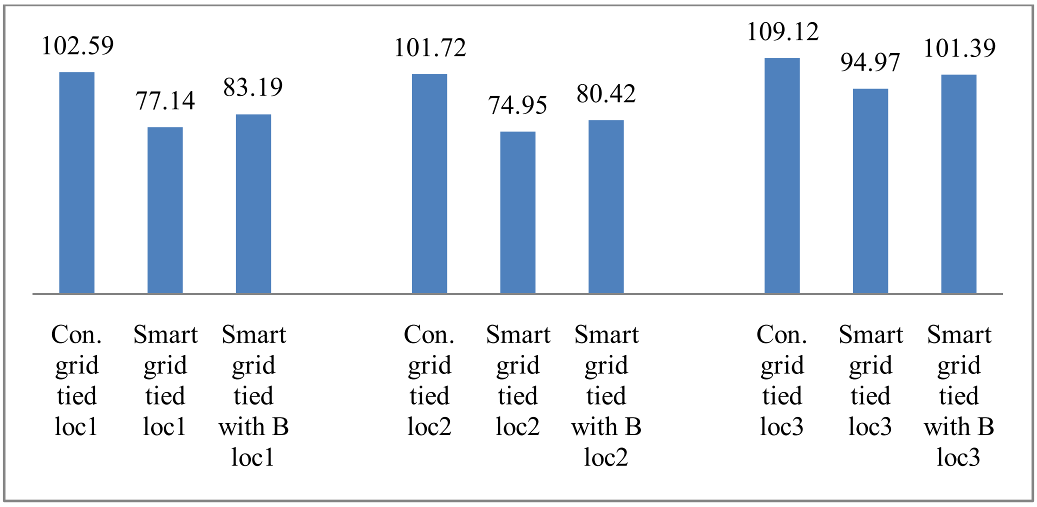


Fig. 7.10 Optimal energy cost in lakh (INR) for three configurations at three locations for load1

The PEC reduces the difference between the life time energy cost of smart grid tied system and smart grid tied system with storage from between 6.37% and 8.15% to between 4.57% and 5.15%. PEC makes the smart grid tied system with storage more acceptable even though its energy cost is higher than smart grid tied system considering its high peak demand reduction and increase in reliability of grid due to less penetration RE at off peak and normal hours. The reduction in cost of storage device and inverter with MPPT controllers for smart grid tied system with storage is required to make the smart grid tied system with storage more financially feasible compared to smart grid tied system even though PEC is provided by the authority.

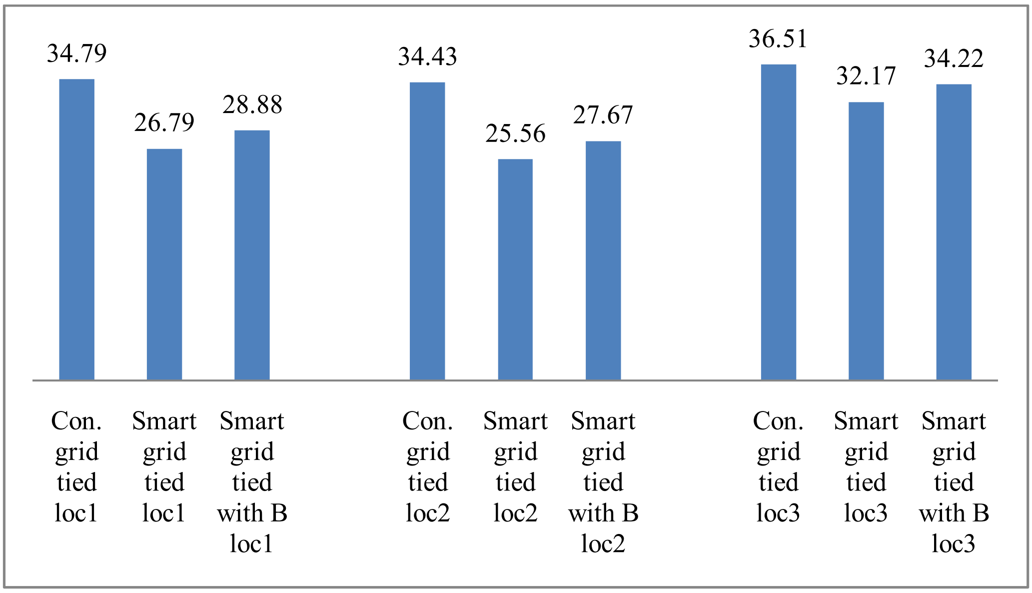


Fig. 7.11 Optimal energy cost in lakh (INR) for three configurations at three locations for load2

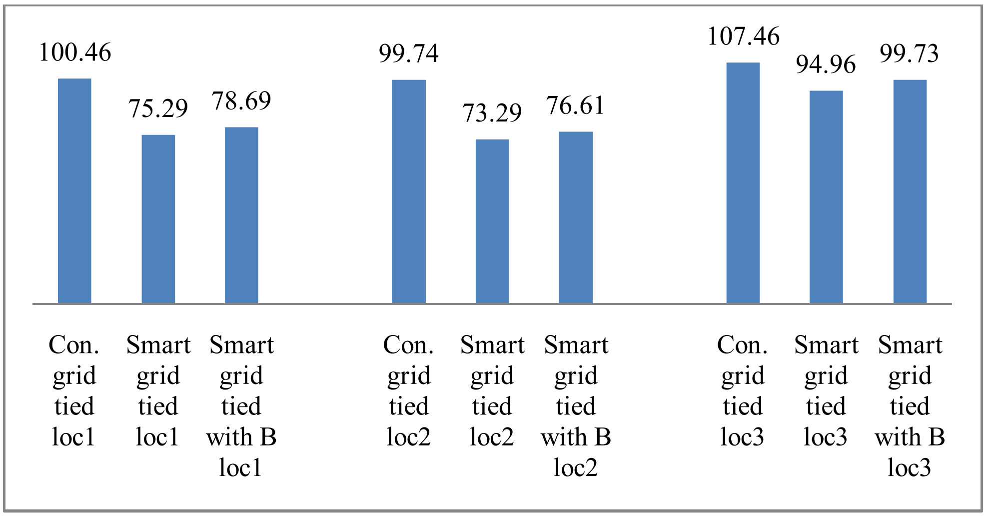


Fig. 7.12 Optimal energy cost with PEC in lakh (INR) for three configurations at three locations for load1

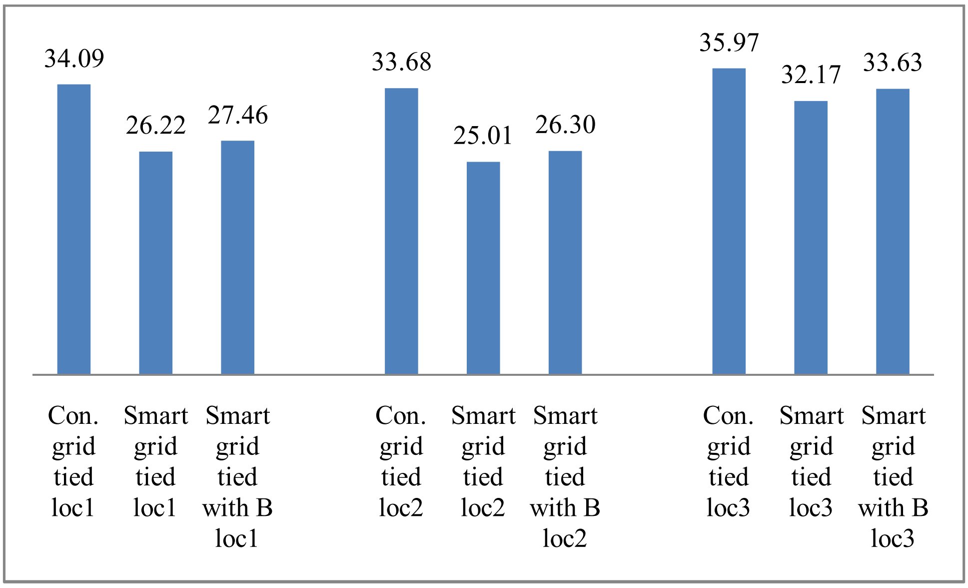


Fig. 7.13 Optimal energy cost with PEC in lakh (INR) for three configurations at three locations for load2

7.3.6 Optimal system

Smart grid tied HPS is more commercially viable with or without PEC and smart grid tied HPS with storage is recommended for peak demand reduction and high reliability of grid. The optimal system configuration for load1 is 1.1kW PV module, 7kW wind mill with 8kW inverted with MPPT controllers and for load2 is 0.7kW PV module, 2kW wind mill with 3kW inverter with MPPT controller at location1. 0.2kW PV module, 7 kW wind mill, 1kW storage battery with 7 kW inverted with MPPT controllers for load1 and 0.7kW PV module, 2kW wind mill, 1kW storage battery with 3kW inverter with MPPT controller for load2 are the optimal smart grid tied system with storage for high peak demand reduction and increasing reliability of grid at location1.

3.4kW PV module and 6kW wind mill with 9kW inverter with MPPT controllers are the optimal HPS for load1 and 1.1kW PV module and 2kW wind mill with 3kW inverter with MPPT controllers are the optimal system for load 2 at location2. 3.4kW PV module and 6kW wind mill, 1kW storage battery with 9kW inverter with MPPT controllers are the optimal HPS for load1 and 1.1kW PV module and 2kW wind mill, 1kW storage battery with 3kW inverter with MPPT controllers are the optimal smart grid tied system with storage for load2 for high peak demand reduction and increasing reliability of grid at location2.

The optimal system for location3 contains only PV module as RES. 7.9kW PV module with 8kW inverter with MPPT controllers is optimal for load1 and 2.5kW PV module with 3kW inverter with MPPT controller is optimal for load2. 7.5kW PV module and 8kW storage battery with 8kW inverter with MPPT controllers and 2.5kW PV module and 3kW storage battery with 3kW inverter with MPPT controller are recommended for optimal smart grid tied HPS with storage for load1 and load2 respectively for high peak demand reduction and increasing reliability of grid at location3.

7.5 Conclusion

The smart grid tied system and smart grid tied system with storage are financially viable if optimal system is chosen. In the case of conventional grid tied system, PEC has to be provided to make the system commercially viable in some locations. RE generation and CO_2 emission reduction are high for smart grid tied system Smart grid tied system with storage is appropriate for high peak demand reduction and to increase reliability of grid with energy cost less than conventional energy cost. The SOC of storage battery is high for this system compared to conventional grid tied system. The optimal energy cost is less for smart grid tied system which is the most financially feasible system. Sensitivity analysis performed on the systems has shown that upward or downward trend in cost will not influence the optimal system arrived at.

Chapter 8

Conclusion, Contribution and Suggestion for Further work

8.1 Conclusion

Developments in conventional energy generation do not meet with increase in demand. Addition of distributed RE generation is one of the solutions to meet energy deficit and peak demand [1]. The decreasing price of RE equipments and increasing cost of fossil fuel will motivate the consumer to go for roof top RES [2]. The GHG emission due to the use of conventional energy resources has been reduced by large scale development of distributed RE generators [16]. T&D loss and requirement of large land area for RES power plant can be addressed by distributed RE generation on roof top [7], [8]. The liberalization of electricity market has also led to speed up the RE generation [2].

This work investigated the economic aspect of installing combination of RES and individual RES for supplementing electrical energy demand in premises. Since economic aspect depends upon energy drawn from grid and energy delivered to grid, the configuration selected are grid tied with unidirectional and bidirectional energy flow. In addition to renewable energy sources energy storage element can also be added to store excess energy generated by RES and to supply during peak hours to reduce peak demand in two configurations. System models and algorithms are developed to determine the optimal system, peak demand reduction and optimal life time energy cost for three configurations. The appropriate constraints for each configuration are taken in implementing the algorithm.

The availability of RE defers from location to location. To test the algorithms three different locations are selected where availability of RE is not identical and in each location two types of demand curve are applied with annual energy consumption which have wide difference.

It is found that the optimal system is HPS for all three configurations at high wind location and PV only system at low wind location. Utilisation of RE is high for smart grid tied system and at high wind location. Smart grid tied system with storage also has high utilisation of RE which is nearer or equal to smart grid tied system. The corresponding CO_2 emission reduction is also achieved.

RE to grid is less for smart grid tied system with storage compared to smart grid tied system for the same utilisation of RE. So grid reliability is enhanced if smart grid tied system with storage is provided. This configuration is also recommend for high peak demand reduction which is more than 85% at high wind location and higher than 37% at low wind location. It also has high SOC for the storage battery which is above71% at high wind location and more than 59% at low wind location compared to near 50% for conventional grid tied system.

It is found that for the given environmental condition roof top RES connected to unidirectional or bidirectional grid can be installed with storage or without storage to meet demand yielding cost less than that of cost of energy drawn from utility. PEC is to be provided for conventional grid tied system in some locations to make the system commercially viable. Smart grid tied system is the most financially feasible system compared to other two systems.

8.2 Research Contribution

- Technical and commercial models for three configurations of HPS detailing energy and cost of energy respectively based on environmental condition are developed. In contrast to the reported works in this area GEC and PEC has been incorporated in the commercial model. The efficiency reduction due to aging during the project life time of the HPS is taken into account in the system technical model.
- Algorithm is developed to find the optimal system either one or both RES to meet demand of the premises with minimum life time energy cost for three configurations of grid connected HPS satisfying the constraints appropriate for each configuration.
- The developed model does not depend on the make, model and type of HPS component. This makes the system model generalised in nature.
- The developed algorithm ensures minimum RE generation and minimum peak demand reduction to ensure REO and flattened demand curve. Limited penetration of RE to grid according to TOD is another advantage of proposed algorithm.
- Technical, economical and environmental factors of three configurations are analysed for individual and combined RES.

- Sensitivity analysis is carried out taking into account variation in cost of utility energy and cost of HPS components which are the most probable varying factors of analysed system.

- Optimal systems of three configurations are compared in terms of RE generation, CO_2 emission reduction, RE to grid, SOC of the storage battery, peak demand reduction and life time energy cost.

- This work assumes to reduce the burden both for the consumer who is willing to generate RE on the roof top of their premises by finding optimal system with minimum life time energy cost and for the utility by limiting the penetration of RE to the healthy level. This clearly indicates the practical usefulness of this research work both for the prosumer and the utility.

8.3 Scope for Further Work

The present work is based on distribution RE generation installed on roof top of buildings. This work may be extended to optimize large scale RES integrated to transmission network or to determine optimal HPS at charging stations provided for electrical vehicle charging. As an extension of this work DSM and real time energy price can be added in the problem formulation. This work assumes linearised models for components of HPS to generalise the models independent of make, model and type. Actually the system characteristics are nonlinear in nature. This may be incorporated in system modelling in future works.

APPENDIX

Table A1 PV module investment

Sl. No	Initial capital cost (ICC)	O&M cost	Installation cost	Reference
1	3.77 $/W			[42]
2	4701 $/kW			[71]
3	250 BDT/W	50 BDT/W/yr		[72]
4	6500 $/kW	65 $/kW		[74]
5	4363 $/kW	82 $/kW		[81]
6	150000 INR/kW	19175 INR/kW		[89]
7	300 $/80W	0		[104]
8	1000 $/0.6kW	2% of ICC	10% of ICC	[10]
9	274 BDT/W			[111]
10	200000 INR/kW	1000 INR/kW/yr		[9]
11	5000 $/kW	0		[112]
12	5000 $/kW			[108]

$=USD, kW=Kilo Watt, yr=Year, BDT=Bangladeshi Taka=77.5$, INR = Indian Rupees=61$

Table A2 Wind mill investment

Sl. No	Initial capital cost (ICC)	O& M cost	Replacement cost	Reference
1	1988 $/kW	0.0026 $/kWh		[71]
2	200000 BDT/kW	10000 BDT/Yr	150000 BDT/kW	[72]
3	3500 $/kW	95 $/kW		[74]
4	1611 $/kW	82 $/kW	1477 $/kW	[81]
5	65000 INR/kW	1000INR/kW/yr		[9]
6	78000 $/30kW			[112]
7	78000 $/30kW			[108]

Table A3 Inverter investment

Sl. No.	Initial capital cost (ICC)	O&M cost	Replacement cost	Reference
1	1363 $/kW			[71]
2	14933 BDT/kW		10000 BDT/kW	[72]
3	1000 $/kW	100 $/kW	1000 $/kW	[81]
4	7500 INR/kW	3195 INR/kW/25yr	0	[89]
5	1000 $/kW	1 $/kW/yr		[104]
6	50000 INR/kW	100 INR/kW/yr		[9]

Table A4 Battery investment

Sl. No.	Initial capital cost (ICC)	O&M cost	Replacement cost	Reference
1	1.26 $/Ah			[40]
2	182 $/kWh	10 $/kWh		[71]
3	7000 BDT/kWh	50 BDT /kWh/yr	6000 BDT/kWh	[72]
4	1500 $/kAh	50 $/kAh/yr	1500 $/kAh	[74]
5	268 $/kW	13 $/kW/yr	268 $/kW	[81]
6	15000 INR/kW	12783 INR/kW/25yr	13113 INR/kW	[89]
7	75 $/1.35kW	2 $/Battery/yr	75 $/1.35kWh	[104]
8	200 $/3.6kW	2% of ICC		[10]

Table A5 Tariff structure of Kerala, India

Sl. No.	Particulars	2013-14		2014-15	
		Energy charge (INR)	Fixed charge (INR)	Energy charge (INR)	Fixed charge (INR)
1	Commercial greater than 500 unit	9.10/kWh	120/kW	9.30/kW	130
2	Industrial	5.10/kWh	60/kW	6.00/kWh	75/kW
3	Domestic greater than 500 unit	7.00/kWh	60/month	7.25/kWh	80/month

Table A6 Initial capital investment of HPS components

Initial Capital Investment in INR				
Rating in kW	**PV module**	**Wind mill**	**Inverter with MPPT controller**	**Storage battery**
1	72000	71500	28000	10000
2	144000	116500	56000	20000
3	216000	196500	84000	30000
4	288000	278000	112000	40000
5	360000	359500	130000	50000
6	432000	425400	148000	60000
7	504000	499100	166000	70000
8	576000	576800	182000	80000
9	648000	646500	213600	90000
10	720000	720200	236200	100000

Table A7 Hourly input data for one day in location1

Sl. No.	Irradiation	Temperature of PV cell	Wind speed
1	0.00	25.00	3.10
2	0.00	25.00	3.30
3	0.00	25.00	1.20
4	0.00	25.00	2.30
5	0.00	25.00	1.80
6	0.00	25.00	3.20
7	0.00	29.00	2.50
8	132.00	33.00	2.50
9	363.00	40.00	2.00
10	567.00	50.00	1.90
11	745.00	60.00	6.30
12	848.00	60.00	7.50
13	876.00	60.00	6.20
14	828.00	60.00	4.60
15	709.00	55.00	2.40
16	530.00	45.00	3.70
17	310.00	33.00	3.30
18	83.00	29.00	1.00
19	0.00	25.00	2.00
20	0.00	25.00	2.90
21	0.00	25.00	4.40
22	0.00	25.00	3.80
23	0.00	25.00	4.20
24	0.00	25.00	4.30

Table A8 Hourly input data for one day in location2

Sl. No.	Irradiation	Temperature of PV cell	Wind speed
1	0.00	26.70	6.20
2	0.00	26.70	5.30
3	0.00	26.70	5.30
4	0.00	26.70	6.00
5	0.00	26.70	6.80
6	0.00	26.70	8.00
7	35.00	30.70	8.30
8	248.00	34.70	8.90
9	492.00	41.70	8.50
10	705.00	51.70	7.10
11	861.00	61.70	5.10
12	951.00	61.70	3.00
13	959.00	61.70	3.00
14	883.00	61.70	4.40
15	718.00	56.70	4.80
16	497.00	46.70	2.70
17	319.00	34.70	6.30
18	45.00	30.70	4.60
19	0.00	26.70	7.40
20	0.00	26.70	9.10
21	0.00	26.70	9.30
22	0.00	26.70	8.10
23	0.00	26.70	7.30
24	0.00	26.70	8.70

Table A9 Hourly input data for one day in location3 for load1

Sl. No.	Irradiation	Temperature of PV cell	Wind speed
1	0.00	27.30	2.17
2	0.00	27.30	2.29
3	0.00	27.30	2.42
4	0.00	27.30	2.39
5	0.00	27.30	2.45
6	0.00	27.30	2.19
7	0.00	31.30	2.31
8	112.00	35.30	2.29
9	325.00	42.30	2.14
10	530.00	52.30	2.01
11	711.00	62.30	2.02
12	817.00	62.30	2.24
13	830.00	62.30	2.68
14	700.00	62.30	3.22
15	624.00	57.30	3.61
16	499.00	47.30	3.82
17	312.00	35.30	3.87
18	96.00	31.30	3.89
19	0.00	27.30	3.77
20	0.00	27.30	3.56
21	0.00	27.30	3.41
22	0.00	27.30	3.26
23	0.00	27.30	3.15
24	0.00	27.30	3.03

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