

**MODELLING OF DECENTRALIZED ENERGY SYSTEMS FOR
DIFFERENT APPLICATIONS IN NORTH-EAST INDIA**

THESIS SUBMITTED BY
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STATEMENT OF ORIGINALITY

I **Abhinandan Baruah** registered on 14.06.2019 do hereby declare that this thesis entitled “**MODELLING OF DECENTRALIZED ENERGY SYSTEMS FOR DIFFERENT APPLICATIONS IN NORTH-EAST INDIA**” contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the “Policy on Anti Plagiarism, Jadavpur University, 2019”, and the level of similarity as checked by iThenticate software is 3 %.

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I dedicate this work to my newly born baby girl Siddhiksha Baruah (Nivi).



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VITA

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ABSTRACT

This work investigated the feasibility of decentralized energy systems (DESs) for resource-rich but grid-outage ridden North-Eastern region of India with an emphasis on the Rangpo area of Pakyong district, Sikkim. The demand of the region is already met by the grid whose major contributing source comprise of the renewable mega hydro power of the Teesta River. However, the unreliable energy supply scenario due to frequent grid outages caused by the complex topography and frequent natural calamities and the long history of damages to life and property caused by the mega-hydropower projects in the region has driven this investigation.

The investigation consisted of five case-studies mainly governed by the location, the type of load demand, the resource availability and the end-use. HOMER Pro Microgrid Tool, developed by the National Renewable Energy Laboratory, United States of America was used as the primary modelling software for the investigation in each of the case-studies. Additionally, innovative techniques, software tools and methods, specific to the needs of each case-study, were also implemented to comprehensively investigate the viability of DESs for each case-study. Further, each case-study also comprised of issues limited to the application or end-use which were investigated and resolved independently. The input parameters were further sensitized for every case-study to realize the viability of DESs over a broader region especially India as a whole.

Case-Study 1 investigated the techno-economic-spatial-environmental feasibility analysis of an off-grid/autonomous hybrid renewable energy system (HRES) for providing electricity to an academic township in the Pakyong District of Sikkim, India. The resources considered for the system were solar energy, wind energy, biogas, syngas and hydrokinetic energy with batteries as back-up. Load demand in the form of real-time hourly data was available for the township. Various constraints were implemented to limit the maximum installation capacities of the components considered. All the technical and financial specifications of the components were availed from the local Indian markets. A total of 31 possible combinations of the different resources were analyzed for net present cost, Levelized cost of energy, battery storage, emissions, area requirements and employment potential. The best combination was identified by applying a very prominent multi-criteria decision-making (MCDM) technique named Analytical Hierarchy Process. The Photovoltaic-Wind-Biogas-Syngas-Hydrokinetic-Battery based Hybrid Renewable Energy System was found to be the best combination with a Levelized Cost of Energy (LCOE) of 0.095 \$/kWh. Finally, sensitivity analysis was carried out for various parameters to comprehend the behavior of the system for a broader application in the region.

Case-Study 2 investigated the techno-economic viability of an off-grid hybrid renewable energy system (HRES) comprising of solar photovoltaic panels (solar energy) and wind turbines (wind energy) as main supply with Lead Acid Batteries (LABs) as back-up for electrification of a grocery shop located at Majhitar area of Sikkim, India. Remote-Areas Multi-energy-systems-load Profiles (RAMP) software was used to promptly generate the stochastic demand data for the shop located in an unreliable electricity area which was imported to HOMER PRO software for simulation on a minute-by-minute basis for determination of LCOE. It was observed that the PV-Battery based system came out to be the best system with an LCOE of 0.311 US \$/kWh while the Wind-Battery based system came out to be the worst system. Sensitivity analysis with respect to climatic conditions across entire India was conducted for the cheapest configuration to comprehend the LCOE for such a load profile across the country. None of the systems were found to be competitive to existing grid prices. However, it has been proposed that with subsidies or with further reduction in PV panel prices the cost of PV-Battery systems may become competitive with grid prices in future.

Case-Study 3 investigated the techno-economic-spatial feasibility of an off-grid rooftop photovoltaic nanogrid (solar energy) for residential sector in the cosmopolitan urban locality of Rangpo, Sikkim, India with unreliable electricity. RAMP was used for load modelling and an innovative technique for spatial feasibility analysis was implemented. 269 houses were surveyed and innovatively classified, based on number of dwelling rooms and demand profile similarity. Correlation and sensitivity analysis were conducted to understand the impact of individual and grouped load profiles, plinth area

per household, number of dwelling rooms, climatic conditions, building types and component specification availability in market on the overall cost, configuration and feasibility of the system. Sharing of photovoltaic nanogrids and higher durations of daily occupancy in houses reduce the Levelized Cost of Energy (LCOE) from the system due to reduction in percentage variations of load. The LCOE of shared nanogrids ranged between 0.151 \$/kWh to 0.195 \$/kWh in India. The study recommended 50 % subsidy on system capital cost against grid prices. Batteries operated at higher Depth of Discharge (DOD) and having longer life at higher DOD reduced the system LCOE. Apartments in locations with high annual solar radiation, low annual temperatures, large plinth area, low monthly demand and unobstructed rooftops were found to be good candidates for PV nanogrids. The study also realized that in India, high-rise buildings with monthly loads up to 30 kWh/household, mid-rise buildings with loads up to 50 kWh/household, low-rise buildings with loads up to 100 kWh/household and double-storey buildings with loads up to 200 kWh/household can successfully adopt autonomous rooftop PV nanogrids.

Case-Study 4 is an extension of the work done in Case-study 3 and conducted a techno-economic investigation to identify the changes in configuration an off-grid renewable energy system comprising of Solar Photovoltaic Panels (solar energy) as main supply with battery as back-up for electrification of a house situated in a location with unreliable electric supply named Borjhar, Guwahati, Assam, India. RAMP software was used to generate the demand data for simulation using HOMER PRO software on a minute-by-minute basis for determination of net present cost and levelized cost of energy. It was observed that the load profile varied considerably with changes in the user behavior including the change in load factor and peak demand. For the system configuration, simulations for annual power demand with higher load factor, lower day-to-day percentage variations and higher daily load demand provided a lower levelized cost of energy compared to annual power demand with lower load factor, higher day-to-day percentage variations and lower daily load demand. This is the only Case-Study conducted outside of Sikkim in the North Eastern Region and spatial investigation has been not considered.

Case-Study 5 investigated the techno-economic-spatial-environmental feasibility of a Rooftop Photovoltaic System (RTPVS) for electrification of a grid outage-ridden, space-restricted public school in Chanatar, Pakyong, Sikkim and the techno-economic impact of electric cooking (e-cooking) against gas cooking to tackle rising Liquefied Petroleum Gas (LPG) prices used in Pradhan Mantri Poshan Shakti Nirman (PM POSHAN) scheme, for enhancing student enrolment in public schools. RAMP was used for load modelling and PVsyst for estimating maximum Photovoltaic panel capacity and optimum Performance Ratio (PR) which were then imported to HOMER PRO for techno-economic investigation. 5 Dispatch Strategies (DSs) were implemented for three RTPVS configurations including two customized HOMER PRO-MATLAB DSs for the grid-connected configurations to understand the impact of employment of advanced and traditional grid-tied and hybrid converters during grid outages. Further, the impacts of transitioning to energy-efficient appliances, grid unreliability and various sensitivity parameters on the modelled system outcomes were also investigated to generate broader comprehension of the system performance. For unreliable grid, PV-grid-battery configuration with grid sales yielded the best feasible result with a lower Global Warming Potential (GWP) and a reduced Levelized Cost of Energy (LCOE) at 0.0548 \$/kWh than both the presently implemented grid-diesel generator (DG)-LPG configuration at 0.306 \$/kWh and prevalent grid-battery configuration at \$0.212 \$/kWh, while the standalone PV-battery configuration is also economically competitive at 0.269 \$/kWh with the least GWP. The PV-grid-battery configuration also showed economic viability across entire India for various component costs, grid tariffs and climatic conditions. The optimum converter capacity was conflictingly impacted by grid sales and converter costs. The advanced hybrid converter despite their high costs will be economically more viable over traditional hybrid converters in PV-grid-battery configuration for locations with high frequency and duration of grid outages. The charging of batteries via grid was not recommended as it increased LCOE and system GWP. In locations with high grid tariffs and high percentage sellback rates, the PV-grid-battery configurations can be oversized to increase grid sales and system reliability without impacting the economic viability of the configuration. The degradation of Lead Acid Battery (LABs) increased LCOE and GWP. Policy implementation like carbon credits and subsidies on RTPVS and e-cooking appliances equivalent to LPG may further promote the RTPVS and e-cooking adoption in public schools.

Based on these 5 investigations, it can be comprehended that not all but specific configurations of DESs are technically-economically-spatially and environmentally viable for different applications in Sikkim and the North-east India. For standalone configurations, an HRES comprising of multiple renewable energy resources namely solar, wind, producer gas, biogas and especially hydrokinetic energy is the most viable option due to its low LCOE, low emission, low area requirements. For standalone systems involving mono energy resources, hydrokinetic and solar-based DESs are two of the most promising prospects in this region if energy autonomy is expected out of system in standalone configurations. Wind energy turns out to be very expensive in the region and economically infeasible while biomass and biogas-based systems fail to reach autonomy in the location. Further, hydrokinetic energy generated from a public asset like river for local use may face regulatory restrictions and limitations of site specificness despite being cheap and thus are not likely to be feasible in every location in region. Similar issues will also arise for biomass-based producer gas which is obtained from forest resources. Thus PV-based systems are likely to be the best alternatives in terms of mono energy resources in this region when regulatory restrictions are considered and hydrokinetic energy-based systems are the best when regulatory restrictions are not taken into account. For standalone PV-battery configuration, LCOE can be reduced by sharing the PV-battery configuration with multiple diversified users which is likely to smoothen the demand and also increase the load factor. For grid-connected DESs involving PV with battery-backups, the LCOE will reduce with grid sales. However, duration of grid outages and the type of converter system used plays a significant role in the overall viability of the system as longer outage duration can increase the LCOE and make the systems spatially infeasible.

Implementation of these DESs either in standalone mode or grid-connected mode on a larger scale for various applications like residential sector, market sector, official and school sector and townships across the country will significantly reduce the pressure of demand on the already unreliable and dominantly fossil-fuel based grid in India and reduce the fossil fuel-based imports and also reduce the global warming potential of the grid as a whole in the country. A combined demand of electrified conventional and cooking load can also be possibly met by these DESs if sufficient area is available for their installation of the DESs. The demand management will always remain a critical aspect in design of these systems for individual type of load or end-user, as it can significantly impact the LCOE.

TABLE OF CONTENTS

STATEMENT OF ORIGINALITY	iv
CERTIFICATE FROM THE SUPERVISOR.....	v
ACKNOWLEDGEMENT	vi
VITA	vii
ABSTRACT.....	viii
ABBREVIATIONS	xvi
Chapter 1 Decentralized Energy Systems Modelling-Present Scenario in India and Research Gaps1	
1.1 Introduction.....	1
1.2 Motivation.....	1
1.3 Literature Review.....	2
1.3.1 Location.....	3
1.3.2 Load Demand and End-use	5
1.3.3 Resource Availability and backups.....	18
1.3.4 Details of techniques, software and resource data used for investigations	18
1.3.5 Details of Sources for Technical and Economic Parameters, Constraints and Sensitivity Parameters.....	19
1.3.6 Details of Technical and Economic Output Parameters	20
1.4 Identified Research Gaps	20
1.5 Objectives of the present work.....	29
Chapter 2 Methodology	31
2.1 Selection of Simulation Tool	32
2.2 Selection of Location	32
2.3 Selection of Load Demand.....	32
2.4 Selection of resources	32
2.5 System component design.....	32
2.5.1 Solar Panels	32
2.5.2 Wind Turbine	34
2.5.3 Biomass Electrical Generation Unit.....	34
2.5.4 Hydro-kinetic turbines	35
2.5.5 Battery.....	35
2.5.6 Converter	36

2.6 Modelling of Financial Parameters	36
Chapter 3 Case Study 1: Modeling of an autonomous Hybrid Renewable Energy System for electrification of a township.....	37
3.1 Introduction.....	37
3.2 Methodology	37
3.2.1 Site Description	37
3.2.2 Load data.....	40
3.2.3 Resource Availability Assessment.....	40
3.2.4 System component design and Financial Modelling	42
3.2.5 Technical and Financial Details of Various Equipment of the HRES	42
3.2.6 Constraints	43
3.2.7 Limitations of Methodology.....	47
3.3 Results.....	47
3.3.2 Comparison of Results for different criteria	51
3.3.3 Identification of the best combination based on different criteria	52
3.3.4 Details of the Best Combination	55
3.3.5 Sensitivity Analysis	55
3.4 Discussion.....	58
3.4.1 Possibility of grid parity.....	59
Chapter 4 Case Study 2: Modelling of an autonomous DES for electrification of a Grocery Shop	61
4.1 Introduction.....	61
4.2 Identification of Site	61
4.3 Generation of Demand Profile for the Shop	61
4.4 Resource Availability.....	62
4.5 System Design and Economic Modelling.....	62
4.6 Technical and Economic Specifications of Various Equipment of the HRES	63
4.7 Results.....	63
4.7.1 Generation of Load Data Using RAMP	63
4.7.2 HOMER PRO Simulation Results	63
4.8 Sensitivity Analysis	65
4.9 Discussion.....	66
Chapter 5 Case Study 3. Modelling of an autonomous roof-top PV nanogrid system for electrification of residential demand.....	67
5.1 Introduction.....	67
5.2 Methodology	67

5.2.1 Selection of Simulation Tool and Location.....	68
5.2.2 Sampling Technique for generation of load profile	68
5.2.3 Classification of households into Categories	72
5.2.4 Modelling of Load Data.....	72
5.2.5 Resource Assessment.....	76
5.2.6 System Component and Economic Modelling.....	76
5.3 Results.....	80
5.3.1 Simulation Results of HOMER PRO	80
5.3.2 Correlation Analysis	80
5.3.3 Rooftop Space Feasibility.....	81
5.3.4 Subsidy for Competitiveness with grid	82
5.3.5 Sensitivity Analysis	82
5.4 Limitations of Methodology	85
5.5 Discussion.....	86
Chapter 6 Case-Study 4. Impact assessment of changes in appliance user behavior on configuration of an off-grid DES for electrification of a residential demand.	91
6.1 Introduction.....	91
6.1.1 Problem.....	91
6.2 Methodology.....	91
6.3 Identification of Site	91
6.4 Generation of Demand Profile for the Conditions	92
6.5 Resource Availability.....	92
6.6 System Design	93
6.7 Technical and Economic Specifications of Various Equipment of the HRES	94
6.8 Results.....	94
6.8.1 Generation of Load Data Using RAMP for Condition 1.....	94
6.8.2 Generation of Load Data Using RAMP for Condition 2.....	95
6.8.3 HOMER PRO Simulation Results	96
6.9 Discussion.....	96
Chapter 7 Case-Study 5: Modeling of a rooftop solar photovoltaic system for electrification of a public school.	99
7.1 Introduction.....	99
7.1.1 Problem.....	99
7.1.2 Salient Literature Reviews in the context of the case-study	100
7.1.3 Research Gaps, Objectives and Novelty.....	102

7.2 Methodology	103
7.2.1 Software Selection	103
7.2.2 Site Selection.....	104
7.2.3 Load Data Generation	105
7.2.4 Performance Ratio Modelling Using PVsyst.....	107
7.2.5 Resource Assessment, Component Specification Details and Constraints.....	109
7.2.6 Grid outage Modelling	110
7.2.7 DSs.....	111
7.2.8 Limitations of Methodology.....	116
7.3 Results and Discussion	116
7.3.1 Demand Load Generation by RAMP and HOMER PRO	116
7.3.2 Results from PVsyst.....	116
7.3.3 Results generated by HOMER Pro.....	118
7.3.4 Impact of different load profiles on LCOE.....	118
7.3.5 Economic feasibility analysis of technical and spatially feasible configurations	119
7.3.6 Environmental viability analysis of the technically, economically and spatially feasible configurations	121
7.4 Validation of Results.....	122
7.4.1 Validation of Load Data Generated by RAMP	122
7.4.2 Validation of DS3 and DS5 developed in MATLAB.....	123
7.4.3 Validation of simulation results of PVsyst and HOMER PRO with other literatures.....	124
7.5 Sensitivity Analysis	124
7.5.1 Comparison and significance of the PV-grid configuration DSs.....	124
7.5.2 Impact of grid outage frequency and outage duration on LCOE for PV-grid-battery configuration.....	126
7.5.3 Impact of converter capacity on LCOE.....	127
7.5.4 Impact of PR on LCOE.....	128
7.5.5 Impact of enhancing system reliability on LCOE.....	128
7.5.6 Sensitivity Analysis of Cost Parameters	129
7.5.7 Impact of climatic conditions on LCOE	131
7.5.8 Impact of battery degradation on system performance and environmental sustainability	132
7.6 Discussion.....	133
7.7 Policy Implications	135
Chapter 8 Conclusion.....	137

8.1 Conclusions for Case-Study 1.....	137
8.2 Conclusions for Case-Study 2.....	138
8.3 Conclusions for Case-Study 3.....	138
8.4 Conclusions for Case-Study 4.....	139
8.5 Conclusions for Case-Study 5.....	140
8.6 Overall Conclusion based on the Case-Studies.....	141
8.7 Scope of Future Work.....	142
REFERENCES	143

ABBREVIATIONS

Nomenclature

DES	“Decentralised Energy Systems”
DGS	“Distributed Generation Systems”
HRES	“Hybrid Renewable Energy System”
HOMER	“Hybrid Optimization Model For Multiple Energy Resources”
NREL	“National Renewable Energy Laboratory”
NPC	“Net Present Cost” (\$)
LCOE	“Levelized Cost Of Energy (\$/Kwh)”
GHG	Greenhouse Gas
WT	Wind Turbine
PV	Photo Voltaic
AHP	“Analytical Hierarchy Process”
MCDM	“Multi-Criteria Decision-Making”
RES	Renewable Energy Source
E_{PV}	“Power Output Of The PV Array”
E_{RPV}	“Rated Capacity Of PV Array (Kw)”
g_{PV}	“PV Derating Factor (%)”
\bar{I}_T	“Solar Radiation Incident On The PV Array In The Current Time-Step (Kw/M ²)”
$\bar{I}_{T,STC}$	“Incident Radiation At Standard Test Conditions (Kw/M ²)”
β_P	“The Temperature Co-Efficient Of Power (%/°C)”
T_c	“PV Cell Temperature In Current Time-Step (°C)”
$T_{c,STC}$	“PV Cell Temperature Under Standard Test Conditions (°C)”
T_a	“Ambient Temperature (°C)”
η_{mp}	“Electrical Conversion Efficiency Of The PV Array (%)”
$T_{c,NOCT}$	“Nominal Cell Operating Temperature (°C)”
$T_{a,NOCT}$	“The Ambient Cell Temperature At Which The Nominal Cell Operating Temperature Is Defined (°C)”
$\bar{I}_{T,NOCT}$	“Solar Radiation At Which The Nominal Cell Operating Temperature Is Defined (Kw/M ²)”
α	“Solar Absorptance Of The PV Array”
τ	“Solar Transmittance Of Any Cover Over The PV Array”
$P_{WTG,STP}$	“Wind Power Output At Standard Temperature And Pressure (W)”
U_{hub}	“The Wind Speed At The Hub Height Of The Wind Turbine (M/S)”
U_{anem}	“Wind Speed At Anemometer Height (M/S)”
z_{hub}	“Hub Height Of The Wind Turbine (M)”
z_{anem}	“Anemometer Height (M)”
Q_1	“The Available Energy In Storage At The Beginning Of The Time Step (Kwh)”
ρ_0	“Air Density At Standard Temperature And Pressure (1.225 Kg/M ³)”
Q	“Total Amount Of Energy In The Storage At The Beginning Of The Time-Step (Kwh)”
Q_{max}	“Total Capacity Of The Storage Tank (Kwh)”
I_{max}	“Storage’s Maximum Charge Current (A)”
$\eta_{batt,d}$	“Battery Discharge Efficiency (%)”
$\eta_{batt,rt}$	“Battery Round Trip Efficiency (%)”
$P_{rec,out}$	“Power Output Of The Rectifier (Kw)”
η_{rec}	“Rectifier Efficiency”
P_{DC}	DC Power Input (Kw)
DC	Direct Current
$C_{ann,tot}$	“Annualized Value Of Total Net Present Cost (\$/Yr)”
$CRF(i, R_{proj})$	“Capital Recovery Factor”
i'	“Nominal Interest Rate (%)”
$C_{NPC,tot}$	Total Net Present Cost (\$)

CO ₂	Carbon Dioxide
IRENA	“International Renewable Energy Agency”
AI	Artificial Intelligence
LHV	Lower Heating Value
α_p	“Power Law Exponent”
P_{WTG}	“Wind Turbine Power Output (<i>Kw</i>)”
ρ	“Actual Air Density (<i>Kg/M³</i>)”
g	“Acceleration Due To Gravity (<i>9.81m/S²</i>)”
z	“The Altitude (<i>M</i>)”
T_o	“Standard Temperature (<i>288.16 K</i>)”
R	Gas Constant (<i>287 J/Kgk</i>)
m_i	“Raw Material Available Per Person (<i>Kgs</i>)”
N_i	“Total Number Of Persons In The Campus “
k_{DMi}	“Dry Matter Content In The Raw Material (Total Solids)”
k_{OMi}	“Total Organic Matter Content In The Dry Matter (Volatile Solids)”
v_{Bi}	“Specific Biomass Output From The Organic Matter (<i>M³/Ton</i>)”
E_B	Potential Of The Obtainable Energy From Raw Material (<i>Kwh</i>)
e_{Bi}	“Specific Heat Energy Obtainable From Raw Material (<i>Kwh/M³</i>)”
η_e	“Co-Efficient Of Electrical Efficiency Of The Biomass Generation Unit (%) (The Electrical Efficiency Of The Biomass Generator At Rated Capacity (%))”
T_c	“Total Operation Hours Of The Plant (<i>H</i>)”
P_E	“Generator Output Power (<i>Kw</i>)”
v_{Bi}	“Specific Biomass Output From The Organic Matter (<i>M³/Ton</i>)”
ρ_f	“Density Of The Fuel (<i>Kg/M³</i>)”
P_{gen}	“The Rated Generator Power (<i>Kw</i>)”
F_o	“Generator Fuel Curve Intercept Co-Efficient (<i>M³/H/Rated Kw</i>)”
F_1	“Fuel Curve Slope (<i>M³/H/Output Kw</i>)”
ρ_H	Density Of Water (<i>1000 Kg/M³</i>)
A_H	Turbine’s Flow Facing Area (<i>M²</i>)
V	“Instantaneous Inflow Velocity Over The Turbine’s Flow Facing Area (<i>M/S</i>)”
ρ_f	“Density Of The Fuel (<i>Kg/M³</i>)”
C_P	“Betz Limit For Power Extraction From The Flowing Water (<i>0.59</i>)”
$P_{batt,max,kb}$	“Maximum Power That Can Be Stored By The Two Tank System (<i>Kw</i>)”
$P_{batt,max,mc}$	“Storage Charge Power Corresponding To The Maximum Charge Current (<i>Kw</i>)”
k	“Storage Rate Constant (<i>H⁻¹</i>)”
Δt	“The Length Of The Time Step (<i>H</i>)”
c	“Storage Capacity Ratio (Unitless)”
α_c	“Storage’s Maximum Charge Rate”
N_{batt}	“The Number Of Batteries In The Storage Bank”
V_{nom}	“The Storage’s Nominal Voltage (<i>V</i>)”
$\eta_{batt,c}$	“The Battery Charge Efficiency (%)”
$P_{inv,out}$	“Power Output Of The Inverter (<i>kW</i>)”
η_{inv}	Inverter Efficiency (%)
P_{AC}	AC Power Input (<i>kW</i>)
$P_{batt,max,mc}$	“Storage Charge Power Corresponding To The Maximum Charge Rate (<i>kW</i>)”
AC	Alternate Current
E_{Served}	“Total Electrical Load Served (<i>Kwh/Yr</i>)”
i	“Real Interest Rate (%)”
f	Expected Inflation Rate
CO	Carbon Monoxide
NO _x	Nitrogen Oxide
RAMP	Remote-Areas Multi-energy systems load Profiles
E_{Served}	“total electrical load served (<i>kWh/yr</i>)”

P_{rated}	The power rating of a particular appliance in Watts
t_{max}	total time of use of the appliance in a day in minutes
t_{min}	minimum duration of time for which the appliance is kept on after switch-on event in minutes
t_{maxvar}	percentage of total time of operation that the appliance is subjected to random variability over a given period.
N_{wind}	number of functional windows within the day for the appliance
$t_{start,wind}$	starting time of each functional window
$t_{end,wind}$	ending time of each functional window
$t_{wind,var}$	percentage random variability in the start and ending times of the functional windows over a given period of time
A_{base}	base (floor) area of the house
β^{roof}	“the slope angle of the roof”
U_{ori}	“utilization factor of orientation”
U_{so}	the shadows and obstacle factor including inter-row shadings between PV panels
U_{abs}	the absolute reduction factor due to cultural, religious and design issues, height of the building.
$F_{fl,num}$	Floor Number
$A_{PV,system}$	Area Requirement for the PV system
A_{roof}^{eff}	Effective roof area available for a vertical line of a multi-storeyed building or a detached house
P_{AC}	AC power input (kW)
W1	Window 1
USA	United States of America
BFA	Building Footprint Area Ratio
N_t	the total number of houses in a particular Category
NASA	National Aeronautics and Space Administration
DOD	Depth of discharge
E_n	Rated energy capacity of the battery (kWh)
σ_{sf}	factor of safety of the inverter (kW)
L_{max}	Peak load (kW)
W2	Window 2
LED	Light emitting diode
POWER	Prediction of Worldwide energy resources
N_f	total number of houses in a particular Category that satisfy the condition of space feasibility for that Category.
GOI	Government of India
C_f	the number of charge-discharge cycles to failure”
E_{th}	Battery throughput (kWh)
C_{inv}	Rated capacity of Power Converter (kW)
USA	United States Of America
LPG	Liquified Petroleum Gas
PM	Pradhan Mantri Poshan Shakti Nirman
POSHAN	
DS	Dispatch Scenario
PV	“Photo Voltaic”
MATLAB	Matrix Laboratory
Y_F	“PV generator final energy yield”
Y_R	“Reference yield of the PV generator”
E	“Net Array Energy Output in kWh
CC	Cycle Charging.
LF	Load Following
G	The hourly radiation in W/m^2
H	the PV reference irradiance in hours

AC	Alternating Current
DC	Direct Current

Units

kWh	Kilowatt Hour
MJ	Mega Joule
h	Hour
kg	Kilogram
J	Joule
A	Ampere
yr	Year
s	Second
K	Kelvin
\$	United States Dollar
g	Gram
m	Metre
°C	Degree Celsius
kW	Kilowatt

Dedicated to my family (Deuta, Maa, Mampi, Nivi)

For their endless love, support and encouragement

Chapter 1 Decentralized Energy Systems Modelling-Present Scenario in India and Research Gaps

1.1 Introduction

Energy shortage, unreliability and its impact on climate change persists as a grave issue in developing countries over the world including countries like India (1–5). With increasing concerns towards global warming and fossil fuel depletion, the world community has shifted their attention towards exploration of renewable energy resources in the past two decades. Renewable energy resources being abundantly available and eco-friendly have the potential to provide affordable, sustainable and clean energy to the entire world community and solve the problem of energy deficiency in developing nations (1–5) and particularly at remote locations with complex landscapes (6). The power grids in India mostly rely on mega power plants which detriment the environment in the installed location (7–12). The distributed generation systems (DGSs) or decentralized energy systems (DESSs) (13) are likely to solve these issues as they employ renewable energy sources (RESs), are smaller in capacity and installed near the point of use. The DESSs are classified as microgrids and nanogrids (13). While microgrids are larger in capacity and designed for a larger population; nanogrids are designed for a single building or a house (household) which can also be connected with other nanogrids and shared to form a microgrid (13,14). These DESSs may be either connected to grid and are known as grid-tied DESSs or disconnected from the grid and are known as a standalone/autonomous or an off-grid system. Such systems may employ single renewable energy source or multiple renewable energy sources to meet the load demand. The feasibility of energy systems based on single renewable energy resources is not enough due to their intermittent availability. Such systems may either need a back-up to compensate for their intermittency or alternatively utilize a combination of renewable energy resources to form a hybrid renewable energy system (HRES). A Hybrid renewable energy system employs multiple energy sources, mostly renewable energy resources with back-ups like batteries. The reliance of HRESs on multiple renewable resources to supply energy compensates for the unreliability of single renewable energy resources and also reduces the greenhouse gas (GHG) emissions. Their nearby installations to the demand location significantly reduces the chances of transmission wire losses and eases the access in terms of repair and maintenance.

However, renewable energy systems can also have adverse effects on the biotic and abiotic environment in the implemented locations. For e.g., establishment of large solar power plants on cultivable lands may lead to lower productivity of the land (10,11) and establishment of large solar power plants on forests lands may be detrimental for the environment as a whole due to thermal imbalance leading to deterioration of flora and reduced mobility of fauna (11,12). Wind energy may also impact the environment in form of excessive useful land usage, noise and visual pollution, ecological adversities etc. (12,15). Similarly, biomass production process may involve adverse externalities such as foul odor emission, noise and visual contamination (16). In case of run-of river, hydropower energy, over installation of multiple turbines may lead to detrimental effects on the both the abiotic and biotic riverine environment (17,18). At congested locations, challenges like localized unavailability and government regulations for biomass and hydropower (19,20) are also needed to be taken into account. Hence, DESSs based on renewable energy systems should be installed in a particular location in a judicious way so that they provide a consistently positive effect on the socio-economic and ecological environment in that location and eliminate the drawbacks of mega grids.

1.2 Motivation

The power demand in the state of Sikkim in India is increasing rapidly owing to a massive boom of industrialization along with establishment of numerous big academic institutes in the region during the past two decades due to tax exemptions and the perennial Himalayan River Teesta flowing across the entire state. Consequently, the residential and commercial power demand has also increased drastically with a rapid shift of man power to this region due to high job prospects. The state power

department has not been able to cope up with the rapidly increasing power demand and this has led to regular power shortages and load shedding in the state. Additionally, the state also has a complex terrain with hills and rain forests and is prone to natural calamities leading to frequent damage of transmission wires and transformers along the region. The complex terrain of the region makes the repair and maintenance of transmission systems very difficult and time consuming. Many localities, townships in this region and even big industries rely on diesel generators during these phases of power cuts which are expensive in operation due to reliance on conventional fuel and also increasing the carbon emissions in the region. Drastic climate changes have also occurred in this region with increase in the average annual temperature every year. The large hydropower projects in this region have already led to degradation of agricultural and forests lands (4). Thus, further investment on large hydropower projects is not recommended for this region. Therefore, the idea of implementation of a DES as a substitute to centralized grid supply in the upcoming and already existing residential sector, commercial sector, public utilities and townships in the region has become a promising prospect. Sikkim has a huge scope for installation of DESs owing to abundant availability of solar radiation, reasonable wind speeds, rich micro hydro prospects from waterfalls, promising hydrokinetic flow speed of the river Teesta and abundant biomass availability (21–24). Hence a detailed techno-economic-spatial-environmental feasibility investigation of this possibility is necessary.

One of the most important problem encountered in modeling or techno-economic-spatial analysis of a DES is the optimal design of its components, that is, identifying the best installation configuration and rated capacity of its components comprising of single or different energy resources for continuous electricity supply without any capacity shortage or oversizing, such that the objective functions, which are generally the levelized cost of energy [LCOE] (138,217,218) or Net Present Cost (NPC) are minimized; the constraints include feasibility in terms of area requirements for the system, minimum greenhouse gas (GHG) emissions, higher employment potential, human development and more renewable energy penetration. The term ‘technically feasible’ means the optimally modelled or designed system is able to meet the demand every hour of the day and every day of the year during its lifetime without any shortage in system capacity or ‘capacity shortage’. The term ‘economically feasible’ means the optimally modelled/proposed system is economically competitive with the existing energy supply system and is generally conveyed by the term ‘LCOE’. LCOE is considered as the price at which the system/electricity must be sold to achieve cost-recovery over its life cycle (217). It represents the net present value in terms of \$/kWh (217). For applications prioritizing self-consumption of electricity over selling like residential sector, township, public utilities and commercial sectors, where full cost-recovery is not possible, the LCOE indicates the price in \$/kWh being paid for purchase of electricity and thus a lower LCOE is always better. The ‘spatial feasibility’ is a term introduced by the authors which means the modelled system has sufficient area for installation in the specific location. The term ‘environmental feasibility’ means the operational emission over project period or the life cycle global warming potential (GWP) of the modelled/proposed system is lesser than the corresponding values for the existing energy supply system and should be as minimal as possible. The analysis of such a problem requires several input parameters which are vastly geographic, demographic and end-use specific in nature and significantly impact the output parameters. The problem can be realized with several output parameters.

In India, several such investigations have been conducted in the past one and a half decade. The following sections tries to provide a highlight a comprehensive review on different aspects of the investigations conducted in India and identify the scope of future work.

1.3 Literature Review

Several studies have been conducted for reviewing various aspects of DES modelling, control, optimization, and protection. (25) presented a systematic review of microgrids, highlighting current challenges and future trends. (26) explored the comparison between AC and DC microgrids, while (27,28) reviewed the optimization techniques, including meta-heuristics, used for DES modelling. (29,30) reviewed the guidelines for implementation of DESs while (27–33) discussed the various control techniques, addressing the diverse challenges in microgrid operation. (34,35) examined the protection mechanisms and operational challenges and (36) reviewed the different reactive power

compensation techniques. (37) discussed the challenges and opportunities associated with evolution of microgrids with converter-interfaced generations. (38) reviewed the microgrid design and monitoring approaches for sustainable green energy networks. (39) comprehensively reviewed the role of microgrids in combating climate change. Several bibliographical analyses have also been conducted in microgrid applications (22,40–42).

India has a very large area and significant variations of climate and resource availability across various locations. The climate and resource availability can even vary within a state across regions. Further due to diversity in culture and traditions, the energy end use-behaviour also varies across regions resulting in diverse demand or load profiles which ultimately impact the design aspects of micro-grids or DESs in the regions.

The following section provides a comprehensive review on different aspects of the decentralized energy systems modelling and analysis conducted specifically in India, simultaneously providing an insight to the whole process of decentralized energy systems modelling which includes the various input parameters required in decentralized energy systems modelling and various output parameters needed for having a conclusive action based on the system’s performance and feasibility. The review further identifies the scope of future work based on which the present research work is based.

The various input parameters necessary for decentralized energy systems modelling are discussed below:

1.3.1 Location

The location plays a very important role in decentralized energy systems modelling as the input parameters namely resource availability, climatic conditions, scale of load demand and profile, technical and economic specifications of system components are dependent on the location and vary across locations and thus impacting the output that is the overall system configuration and its economic aspects. Several technical and techno-economic investigations have been conducted across different locations and different parts of world including India (43–50). The number of researches conducted across different states in India is provided in **Figure 1.1**. The highest number of investigations have been conducted in Uttarakhand (UK) at 24 while the least have been conducted for Dadra and Nagar Haveli (DNH) at 1.

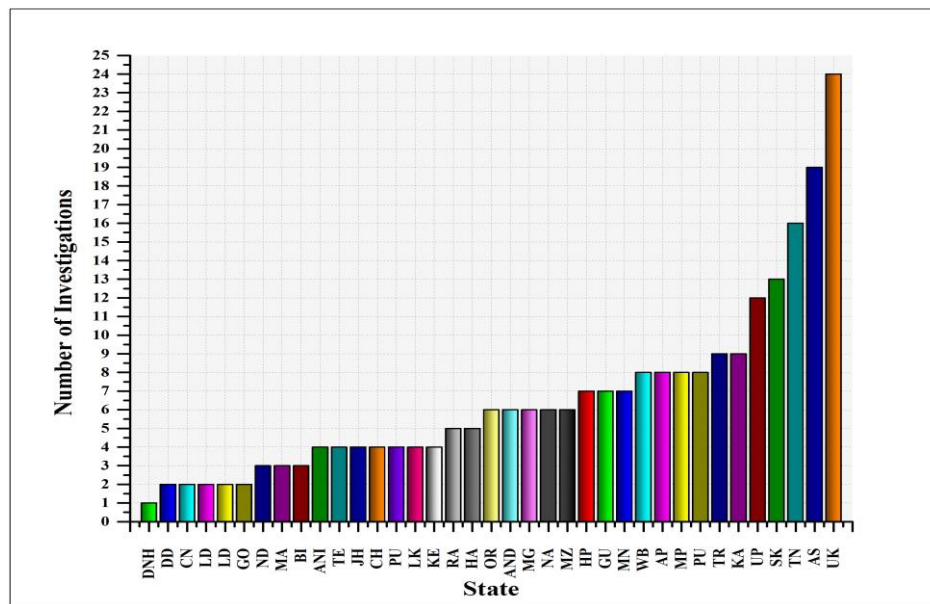


Figure 1.1 The statewise details of investigation

The locations in India where investigation based on decentralized energy systems modelling have been conducted in each state are provided in **Table 1.1**. Though several investigations have been

conducted for North-Eastern region considering the state as a whole region of a particular climatic condition, however very few investigations have been conducted region wise within a state which is significant as the climatic conditions vary from location to location within a state and assuming the state as a single climate region can be a misinterpretation in this context.

Table 1.1 Statewise Details of Investigation

States and Union Territories	References
Andaman & Nicobar Islands	Port Blair (51,52), Baratang (53), Unspecified location(54)
Andhra	Visakhapatnam (55), (Vaddeswaram) Guntur (56), (Doddipalli) Chittoor (57), (Gajuwaka) Visakhapatnam (58), (Amaravati) Guntur (51), Unspecified location (59)
Arunachal Pradesh	Unspecified location (60–64), East Kameng (65) , Siang (66), Itanagar (51)
Assam	Tezpur(67) , Unspecified location (60–64), (Silchar) Cachar (59,68–73), Kamrup (74), Nagaon (75), (Borjhar, Guwahati) Kamrup (76), Dispur (Kamrup Metropolitan) (51)
Bihar	(Hariharpur) Sant Kabir Nagar, (Gurmia) Vaishali, (Gorigama) Muzaffarpur (77), Patna (51), Unspecified location (64)
Chandigarh	Chandigarh (51) , Unspecified location (64)
Chhattisgarh	Palari (78,79) , Raipur (51), Unspecified location (64)
Dadra & Nagar Haveli	Unspecified location (64)
Daman & Diu	Daman (51) , Unspecified location (64)
Delhi	(Unspecified location) New Delhi (51,80), Unspecified location (64)
Goa	Panaji (51), Unspecified location (64)
Gujarat	Banaskantha (81), (Bhuj) Kutch (82), (Dashwada) Valsad (83), (Jakhau) Kutch (84), Gandhinagar (51), Vadodara (85), Unspecified location (64)
Haryana	Ambala (85), Rohtak (86), Yamunanagar (87,88), Unspecified location(64)
Himachal Pradesh	Hamirpur (89–92), Chamba (93), Shimla (51), Unspecified location (64)
Jammu & Kashmir	Jammu (51) , Unspecified location (64)
Ladakh	Leh (51), Unspecified location (64)
Jharkhand	Dhanbad (94), unspecified village (95), Ranchi (51), Unspecified location (64)
Karnataka	(Bengaluru) Bangalore Urban (51), Chamarajanagar (96–99), Chikmagalur (100,101), Belgavi (Balagavi) (85), Unspecified location (64)
Kerala	Thiruvananthapuram (51), (Kakkavayal) Wayanad (102), (Pathanpara) Kannur (102), Unspecified location (64)
Lakshadweep	Andrott, Kavaratti, Kiltan and Minicoy (103), Minicoy (53), Kavaratti (51) Unspecified location (64)
Madhya Pradesh	Bhopal [38, 63, 69, 74, 103], Barwani (104), Sagar (105), Unspecified location (64)
Maharashtra	Mumbai (51), Pune (85), Unspecified location (64)
Manipur	Unspecified location (60–64), Senapati (106), Imphal (51)
Meghalaya	Unspecified location (60–64), (Shillong) East Khasi hills (51)
Mizoram	Unspecified location (60–64), Aizawl (51)
Nagaland	Unspecified location (60–64), Kohima (51)
Odisha	(Muniguda) Rayagada (107,108), (Uperbeda) Mayurbhanj (109), Bhubaneswar (Khordha) (51), Angul (85), Unspecified location (64)
Puducherry	Pondicherry (51), (Korkadu) Pondicherry (110,111), Unspecified location (64)

Punjab	Amritsar, Ludhiana, Patiala, and Chandigarh (112), Ludhiana (113), Patiala (79,114), unspecified village (115), Chandigarh (51), Mohali (85), Unspecified location (64)
Rajasthan	Bhilwara (116), Jaipur (51,85,117), Unspecified location (64)
Sikkim	Unspecified location (60–64), (Rangpo) Pakyong (54,118,119), Gangtok (51)
Tamil Nadu	Kanyakumari (120), Chennai (51,121), Vellore, Salem, Kanyakumari, (Ooty) Nilgiris, Nagapattinam and Thoothukudi (122), (Virudhunagar) Madurai (123), (Kadayam) Tirunelveli (124), (Gudalpur) Nilgiri (125), Thanjavur (126), (Kovilpatti) Thoothukudi (127), (Virudhunagar) Madurai (123), (Pongalur) Tirrupur (128), (Madurai, Ooty, Salem, Chennai, Nagapattinam, Rameswaram, Kanyakumari) (129,130), (Veerasingampettai) Thanjavur (102), Unspecified location(64)
Telangana	Hyderabad (51,85), Karimnagar(131), Unspecified location (64)
Tripura	Unspecified location (60–64,132), Agartala (West Tripura) (51,133,134)
Uttar Pradesh	Ghaziabad (135), Banda (136), Agra (137), Moradabad (138), Varanasi (85,139), Lucknow (51,140,141), Sarai Jairam village (Agra) (142), unspecified hamlets (143), Unspecified location (64)
Uttarakhand	Chamoli (1,2,144–149), Almora (150–156), (Narendra Nagar) Terhi Garhwal (157–160), Uttarkashi(161), unspecified village (162), Dehradun (51), Unspecified location (64)
West Bengal	Kolkata (51,163), Birbhum (164), (Mousuni Island) Sundarbans (165), (Ghoramara island) Sundarbans (54), (Jeliakhali Paschim village) Sundarbans, 24 Paraganas North (166), (Shibpur) Howrah (167), Unspecified location (64)

1.3.2 Load Demand and End-use

The type of load demand plays a very critical role in these investigations as in the scale and profile of load demand which ultimately has a critical role in system design and configuration. The type of load demand includes rural and urban loads which may further be classified into residential, commercial, community, industrial, agricultural, academic loads or a combination of all these loads etc. The details of the load demand are provided in **Table 1.2**. About two-thirds of the investigations have been conducted for rural locations while the remaining one-third of the investigations have been conducted for urban locations. The main motivation for majority of these investigations being conducted in rural locations is due to totally unelectrified locations and expensive possible grid extensions which have resulted in investigation of the feasibility of decentralized systems for these locations.

On the other hand, the main motivation for urban localities has been the unreliable and low quality of electricity which have led to investigation of more reliable alternatives. However, several investigations have been also conducted in earlier published literatures to just investigate the feasibility of a DES for a new type of load demand or end-use. Several literatures have investigated multiple sub-categories of load demand as a grouped load and several investigations have only investigated an individual sub-category of the load demand. However, there are barely any investigations which have tried to identify the implication of individual load demand profiles on the outcome of the system configuration. Similarly, the investigations which have considered individual sub-categories have not investigated implications of variations of individual load profiles within the sub-categories of load demand. The load profiles are strongly governed by the time of use of appliances by the users and can impact the outcome of the system configurations and economic aspects and require further investigation. The end-use is generally in the form of electric end-use for conventional electric appliances which of lately diversified into electric space and water heating, electric cooking, irrigation and electric transportation. The details of the end-use are provided in **Table 1.3**. Most of the investigations have considered conventional electric appliances as end-use. Few investigations have

Table 1.2 Details of Load Demand

Reference	Broad type Of Load Demand	Sub-category of load demand									Investigation of sub-categories (Grouped/Individual)
		Residential	Community	Commercial	Agricultural	Industrial	Academic Building /Laboratory /School	Telecom Load (Base Transceiver Station)	Township (Academic/Tea Estate)	Other	
(1)	Rural	✓	✓	✓	✓	✓	✗	✗	✗	✗	Grouped
(2)	Urban	✗	✗	✗	✗	✗	✗	✓	✗	✗	Individual
(51)	Urban	✓	✗	✗	✗	✗	✗	✗	✓	✗	Individual
(52)	Rural	✗	✗	✗	✗	✓	✗	✗	✗	✗	Individual
(53)	Rural	✗	✗	✗	✗	✓	✗	✗	✗	✗	Individual
(54)	Rural	✓	✓	✓	✗	✗	✗	✗	✗	✗	Grouped
(55)	Urban	✓	✓	✓	✓	✓	✓	✓	✓	✗	Grouped
(56)	Urban	✗	✓	✗	✗	✗	✗	✗	✗	✗	Individual
(57)	Rural	✓	✗	✓	✓	✗	✗	✗	✗	✗	Grouped
(58)	Urban	✓	✗	✓	✗	✓	✗	✗	✗	✗	Grouped
(59)	Rural	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(60)	Urban	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(61)		✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(62)	Urban	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(63)	Urban	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(64)	Urban	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(65)	Rural	✗	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(66)	Rural	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(67)	Rural	✓	✓	✓	✗	✗	✗	✗	✗	✗	Grouped
(68)	Urban	✗	✗	✗	✗	✗	✓	✗	✗	✗	Individual
(69)	Urban	✗	✗	✗	✗	✗	✗	✓	✗	✗	Individual
(70)	Rural	✗	✗	✗	✗	✗	✗	✗	✓	✗	Individual
(71)	Urban	✗	✗	✗	✗	✗	✗	✓	✗	✗	Individual
(72)	Rural	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(73)	Rural	✗	✗	✗	✗	✗	✗	✗	✗	Water Supply System	Individual
(74)	Rural	✓	✗	✗	✓	✗	✗	✗	✗	✗	Grouped
(75)	Rural	✓	✗	✓	✗	✗	✗	✗	✗	✗	Grouped
(76)	Urban	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(77)	Rural	✗	✓	✗	✗	✗	✗	✗	✗	✗	Individual
(78)	Rural	✓	✓	✓	✓	✓	✗	✗	✗	✗	Grouped
(79)	Rural	✓	✓	✓	✓	✓	✗	✗	✗	✗	Grouped
(80)	Urban	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(81)	Rural	✓	✓	✓	✓	✗	✗	✗	✗	✗	Grouped
(82)	Rural	✓	✓	✓	✗	✓	✗	✗	✗	✗	Grouped
(83)	Rural	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(84)	Rural	✓	✗	✗	✗	✗	✗	✗	✗	✗	Individual
(85)	Urban	✗	✗	✗	✗	✗	✗	✓	✗	✗	Grouped
(86)	Urban	✓ (Hostel)	✗	✓	✗	✓	✓ (School, College)	✗	✓ (Vocational residential training institute)	Hospital	Individual
(87)	Rural	✓	✗	✗	✓	✗	✗	✗	✗	✗	Grouped

(88)	Rural	✓	✓	x	x	x	x	x	x	x	x	Grouped
(89)	Urban	x	x	x	x	x	✓	x	x	x	x	Individual
(90)	Urban	x	x	x	x	x	x	x	✓	x	x	Individual
(91)	Urban	x	x	x	x	x	✓	x	x	x	x	Individual
(92)	Urban	x	x	x	x	x	✓	x	x	x	x	Individual
(93)	Rural	✓	✓	✓	x	x	x	x	x	x	x	Grouped
(94)	Rural	x	✓	x	x	x	x	x	x	x	x	Individual
(95)	Rural	✓	x	x	✓	x	x	x	x	x	x	Grouped
(96)	Rural	✓	✓	x	✓	x	x	x	x	x	x	Grouped
(97)	Rural	✓	✓	✓	x	✓	x	x	x	x	x	Individual
(98)	Rural	✓	✓	✓	x	x	x	x	x	x	x	Grouped
(99)	Rural	✓	✓	✓	x	x	x	x	x	x	x	Grouped
(100)	Rural	✓	✓	✓	✓	x	x	x	x	x	x	Grouped
(101)	Rural	✓	✓	✓	✓	✓	x	x	x	x	x	Grouped
(102)	Rural	✓	x	✓	x	x	x	x	x	x	Institutional	Individual
(103)	Rural	x	x	x	x	x	x	x	x	x	Whole island	Individual
(104)	Rural	✓	✓	✓	x	✓	x	x	x	x	x	Grouped
(105)	Urban	x	x	x	x	x	x	x	x	x	Auditorium of	Individual
(106)	Rural	✓	✓	✓	x	✓	x	x	x	x	x	Grouped
(107)	Rural	✓	✓	✓	✓	x	x	x	x	x	Reverse Osmosis	Grouped
(108)	Rural	✓	x	x	✓	x	x	x	x	x	Desalination	Grouped
(109)	Rural	✓	x	x	✓	x	x	x	x	x	x	Grouped
(110)	Rural	✓	✓	✓	✓	✓	x	x	x	x	x	Grouped
(111)	Rural	✓	✓	✓	✓	✓	x	x	x	x	x	Grouped
(112)	Urban	x	x	x	x	x	x	✓	x	x	x	Individual
(113)	Urban	✓	x	x	x	x	x	x	x	x	x	Individual
(114)	Rural	x	✓	x	x	x	x	x	x	x	x	Individual
(115)	Rural	✓	x	x	x	x	x	x	x	x	x	Individual
(116)	Urban	✓	✓	✓	x	x	x	x	x	x	x	Grouped
(117)	Urban	✓	x	✓	x	x	x	x	x	x	x	Grouped
(118)	Urban	x	x	x	x	x	x	x	✓	x	x	Grouped
(119)	Urban	x	x	✓	x	x	x	x	x	x	x	Individual
(120)	Urban	✓	x	x	x	x	x	x	x	x	x	Individual
(121)	Rural	✓	✓	✓	x	x	x	x	x	x	x	Grouped
(122)	Urban	✓	x	x	x	x	x	x	x	x	x	Individual
(123)	Urban	x	x	x	x	x	x	x	✓	x	x	Individual
(124)	Rural	✓	x	x	✓	✓	x	✓	x	x	x	Grouped
(125)	Rural	x	x	x	x	✓	x	x	x	x	x	Individual
(126)	Rural	✓	x	✓	x	x	x	x	x	x	x	Grouped
(127)	Rural	✓	x	x	x	x	x	x	x	x	x	Individual
(128)	Rural	✓	x	x	x	x	x	x	x	x	x	Individual
(129)	Rural	✓	x	✓	x	x	x	x	x	x	Public Utility	Grouped
(130)	Rural	✓	x	✓	x	x	x	x	x	x	x	Grouped
(131)	Rural	✓	x	x	x	x	x	x	x	x	x	Individual
(132)	Rural	x	x	x	x	✓	x	x	x	x	x	Individual
(133)	Urban	x	x	x	x	x	✓	x	x	x	x	Individual
(134)	Rural	x	x	x	x	✓	x	x	x	x	x	Individual

(135)	Urban	✓	×	×	×	×	×	×	×	×	×	Individual
(136)	Urban	✓ (Hostel)	×	×	×	×	×	×	×	×	×	Individual
(137)	Urban	×	×	×	×	×	×	×	✓	×	×	Individual
(138)	Rural	✓	×	×	×	×	×	×	×	×	×	Grouped
(139)	Rural	✓	×	✓	×	×	×	×	×	×	×	Institutional
(140)	Rural	✓	×	×	×	×	×	×	×	×	×	Individual
(141)	Urban	✓	×	×	×	×	×	×	×	×	×	Individual
(142)	Rural	×	✓	×	×	×	✓	×	×	×	×	Grouped
(143)	Rural	✓	×	×	×	×	×	×	×	×	×	Individual
(145)	Rural	✓	✓	✓	✓	×	×	×	×	×	×	Grouped
(146)	Rural	✓	✓	✓	×	×	×	×	×	×	×	Grouped
(147)	Rural	✓	×	×	×	×	×	×	×	×	×	Individual
(148)	Rural	✓	✓	✓	✓	×	×	×	×	×	×	Grouped
(149)	Rural	✓	×	×	✓	×	×	×	×	×	×	Grouped
(150)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(151)	Rural	✓	✓	×	✓	✓	×	×	×	×	×	Grouped
(152)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(153)	Rural	✓	✓	×	✓	✓	×	×	×	×	×	Grouped
(154)	Rural	✓	×	×	×	×	×	×	×	×	×	Individual
(155)	Rural	✓	×	×	×	×	×	×	×	×	×	Individual
(156)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(157)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(158)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(159)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(160)	Rural	✓	✓	✓	×	✓	×	×	×	×	×	Grouped
(161)	Urban	✓	×	×	×	×	×	×	×	×	×	Individual
(162)	Rural	✓	✓	✓	✓	×	×	×	×	×	×	Grouped
(163)	Urban	×	×	×	×	×	×	×	✓	×	×	Individual
(164)	Rural	×	×	×	×	×	×	×	×	×	×	Grouped
(165)	Rural	✓	✓	✓	×	×	×	×	×	×	×	Grouped
(166)	Rural	✓	×	×	×	×	×	×	×	×	×	Individual
(167)	Urban	×	×	×	×	×	×	✓	×	×	×	Grouped
(168)	Urban	×	×	×	×	×	×	✓	×	×	×	Individual
(169)	Rural	✓	✓	✓	✓	×	×	×	×	×	×	Grouped
(170)	Urban	×	×	×	×	×	×	×	×	✓	×	Individual
(171)	Rural	✓	×	✓	✓	×	×	×	×	×	×	Grouped
(172)	Rural	✓	✓	×	✓	✓	×	×	×	×	×	Grouped

Table 1.3 .Details of End-Use

Reference	Type of end-use	Type of demand data generated	Peak Load Demand (kW)	Percentage day-to-day load variations (%)	Percentage time step variation (%)	Load Factor
(1)	Conventional Electricity with electric water heating	Survey-based synthetic data	not known	not known	not known	not known
(2)	Conventional Electricity	Survey and Assumption based synthetic data	not known	not known	not known	not known
(51)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(52)	Conventional Electricity	Assumption-based synthetic data	given (1.13 kW)	Given (10%)	Given (15%)	given (5.19 kWh/day)

(53)	Conventional Electricity	Assumption-based synthetic data	given (0.4 kW)	Given (10%)	Given (20%)	given (0.21)
(54)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(55)	Conventional Electricity	Real demand data	not known	not known	not known	not known
(56)	Conventional Electricity	Survey-based synthetic data	given (214 KW)	not known	not known	given (714 kwh/day)
(57)	Conventional Electricity	Survey-based synthetic data	given (12.7 kW)	not known	not known	given (0.28)
(58)	Conventional Electricity	Survey-based synthetic data	Not given	Not given	Not given	Not given
(59)	Conventional Electricity	Survey-based synthetic data	given (100.02 kW)	Not given	Not given	Given (0.41)
(60)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(61)	Conventional Electricity	Assumption-based synthetic data	given (0,575)	Given (2.02)	Given (12.02)	Given (10 kw)
(62)	Conventional Electricity	Assumption-based synthetic data	given (1.13 kW)	Given (15%)	Given (20%)	load factor (0.192)
(63)	Conventional Electricity	Assumption-based synthetic data	given (694 W)	not known	not known	load factor (3.95 kwh/day)
(64)	Conventional Electricity	Survey and software-based synthetic data	given (0.8 kW)	Not given (4.42)	Not given (12.75)	Given (0.31)
(65)	Conventional Electricity with cooking (but details not provided)	Survey-based synthetic data	given	not known	not known	not known
(66)	Conventional Electricity with electric water heating	Survey-based synthetic data	given	not known	not known	Given
(67)	Conventional Electricity	Assumption-based synthetic data	given	not known	not known	Given
(68)	Conventional Electricity	Survey-based synthetic data	given	considered (2%)	considered (2%)	Given
(69)	Conventional Electricity	Real demand data	given	not considered	not considered	Given
(70)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(71)	Conventional Electricity	Real demand data	given	given (5%)	given (5%)	Given
(72)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(73)	Conventional Electricity	Survey-based synthetic data	given	Given (10%)	Given (15%)	Given
(74)	Conventional Electricity	Assumption-based synthetic data	Given	Not given	Not given	Not given
(75)	Conventional Electricity	Assumption-based synthetic data	given	Not given	Not given	given
(76)	Conventional Electricity	Survey and software-based synthetic data	given (5.46 kW)	Not given (9.24)	Not given (95.71)	Given (0.07)
(77)	Conventional Electricity	Assumption-based synthetic data	given (2kW)	Not given	Not given	not known
(78)	Conventional Electricity	Assumption-based synthetic data	given	not known	not known	Given
(79)	Conventional Electricity	Survey-based synthetic data	Given (102 kW for village 1, 39.4 kW for village 2, 68.6 kW for deferred load)	Not given	Not given	Given (Avg Load. 222.0 kWh/day for village 1, Avg Load. 212.5 kWh/day for village 2, Avg Load. 58.0 kWh/day for village 1)
(80)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	not given
(81)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(82)	Conventional Electricity	Survey-based synthetic data	given (226 kW) during summer and (285 kW) during winter	not known	not known	not known
(83)	Conventional Electricity	Assumption-based synthetic data	Given	Not given	Not given	Not given
(84)	Conventional Electricity	Survey-based synthetic data	Not given	Not given	Not given	Not given
(85)	Conventional Electricity	Real demand data	not known	not known	not known	not known
(86)	Conventional Electricity	Real demand data	not known	Not given	Not given	not known
(87)	Conventional Electricity with electric heating and ice making	Survey-based synthetic data	Given	Not given	Not given	Not given
(88)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	not given (avg load)
(89)	Conventional Electricity	Real demand data	not known	not known	not known	not known
(90)	Conventional Electricity	Real demand data	given (0.125)	not known	not known	given (29.2)
(91)	Conventional Electricity	Real demand data	given (29.2)	Not given	Not given	given (0.125)
(92)	Conventional Electricity	Real demand data	Given	Not given	Not given	given
(93)	Conventional Electricity	Survey-based synthetic data	not given	Not given	Not given	not given

(94)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(95)	Conventional Electricity	Survey-based synthetic data	not given	Not given	Not given	not given
(96)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(97)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(98)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	Not given
(99)	Conventional Electricity	Survey-based synthetic data	the total load is given	Not given	Not given	not given (avg load)
(100)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(101)	Conventional Electricity	Survey-based synthetic data	Not given	Not given	Not given	Not given
(102)	Conventional Electricity	Survey-based synthetic data	Given	Not given	Not given	Given (primary load per day)
(103)	Conventional Electricity	Survey-based synthetic data	not given	Not given	Not given	not given
(104)	Conventional Electricity	Survey-based synthetic data	given (7.8)	Not given	Not given	given (4.61)
(105)	Conventional Electricity	Survey-based synthetic data	given (2.5)	Not given	Not given	given (18 kWh/day)
(106)	Conventional Electricity	Survey-based synthetic data	not given	Not given	Not given	not given
(107)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(108)	Conventional Electricity	Assumption-based synthetic data	given	Not given	Not given	Not given
(109)	Conventional Electricity	Survey-based synthetic data	Survey-based synthetic data	Not given	Not given	Given
		Artificial Neural Network (ANN), Adaptive Neuro Fuzzy Interference System (ANFIS), Recurrent Neural Network (RNN)+ Long Short-Term Memory (LSTM) for load forecasting	given			
(110)	Conventional Electricity	Survey-based synthetic data	Not given	Not given	Not given	not given
(111)	Conventional Electricity	Assumption-based synthetic data	not given	Not given	Not given	not given
(112)	Conventional Electricity	Survey-based synthetic data	Given (1.12 kW)	Not given	Not given	Given (0.42)
(113)	Conventional Electricity	Survey-based synthetic data	given (0.2)	not known	not known	given (2.55)
(114)	Conventional Electricity	Survey-based synthetic data	given (102 kw)	Not given	Not given	given (0.406)
(115)	Conventional Electricity	Survey-based synthetic data	given (275 kwh)	Not given	Not given	given (0.463)
(116)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(117)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	not given (avg load)
(118)	Conventional Electricity	Real demand data	given (632 kW)	Not given	Not given	Given (0.62)
(119)	Conventional Electricity	Survey and software-based synthetic data	given (1.03 kW)	Not given (20.596)	Not given (91.695)	Given (0.21)
(120)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(121)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(122)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(123)	Conventional Electricity	Real demand data	not known	not known	not known	not known
(124)	Conventional Electricity	Survey-based synthetic data	given (12.7 kW)	not known	not known	given (0.978)
(125)	Conventional Electricity along with thermal load and hydrogen load	Survey-based synthetic data	not known	not known	not known	not known
(126)	Conventional Electricity	Survey-based synthetic data	given	Given (10%)	Given (10%)	not given
(127)	Conventional Electricity	Assumption-based synthetic data	given	Not given	Not given	Given
(128)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	Not given (avg load)
(129)	Conventional Electricity	Survey-based synthetic data	Not given	Not given	Not given	given
(130)	Conventional Electricity with electric space heating	Survey-based synthetic data	given	Not given	Not given	given
(131)	Conventional Electricity	Survey-based synthetic data	Given	Not given	Not given	Not given
(132)	Conventional Electricity	Assumption-based synthetic data	given (25 kW)	Not given	Not given	given (25)
(133)	Conventional Electricity	Survey-based synthetic data	not known	considered (15%)	considered (20%)	not known
(134)	Conventional Electricity	Survey-based synthetic data	given (14 kW)	not known	not known	given (92kwh/day)

(135)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(136)	Conventional Electricity	Survey-based synthetic data	given	unknown	unknown	given
(137)	Conventional Electricity	Real demand data	not given	Not given	Not given	not given
(138)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	not given (avg load)
(139)	Conventional Electricity with solar home lighting system	Survey-based synthetic data	given	Not given	Not given	given
(140)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	Not given
(141)	Conventional Electricity	Assumption-based synthetic data	Given	Not given	Not given	Given
(142)	Conventional Electricity	Assumption-based synthetic data	Not given	Not given	Not given	Not given
(143)	Conventional Electricity	Survey-based synthetic data	given	Not given	Not given	not given
(145)	Conventional Electricity with electric water heating	Survey-based synthetic data	not known	not known	not known	not known
(146)	Conventional Electricity	Survey-based synthetic data	given	not known	not known	not known
(147)	Conventional Electricity	Survey-based synthetic data	given (13 kw)	Not given	Not given	not given (218 kwh/day)
(148)	Conventional Electricity	Survey-based synthetic data	given (150.51 kW during summer and 146.52 kW during winter)	Not given	Not given	not known
(149)	Conventional Electricity	Assumption-based synthetic data	Given	Not given	Not given	Not given
(150)	Conventional Electricity	Survey-based synthetic data	not given	Not given	Not given	not given
(151)	Conventional Electricity	Survey-based synthetic data	not known	Given (10%)	Given (20%)	not known
(152)	Conventional Electricity	Survey-based synthetic data	given (102.1 kw in summer and 98.1 kw in winter)	not known	not known	not known
(153)	Conventional Electricity	Survey-based synthetic data	not known	Not given	Not given	not known
(154)	Conventional Electricity	Survey-based synthetic data	given (per season)	Not given	Not given	not given
(155)	Conventional Electricity	Survey-based synthetic data	given (per season)	Not given	Not given	not given
(156)	Conventional Electricity	Assumption-based synthetic data	given	Not given	Not given	given
(157)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(158)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(159)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(160)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(161)	Conventional Electricity	Survey-based synthetic data	given (94.76 kW)	Not given	Not given	given (510.36 kWh/day)
(162)	Conventional Electricity	Survey-based synthetic data	given (35.5)	Not given	Not given	given (0.32)
(163)	Conventional Electricity	Synthetic data based on existing database	not known	not known	not known	not known
(164)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(165)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(166)	Conventional Electricity	Survey-based synthetic data	not known	not known	not known	not known
(167)	Conventional Electricity	Survey-based synthetic data	given (7.5 kW)	not known	not known	not known
(168)	Conventional Electricity	Assumption-based synthetic data	not known	not known	not known	not known
(169)	Conventional Electricity with electric water heating	Survey-based synthetic data	not known	not known	not known	not known
(170)	Conventional Electricity	Survey-based synthetic data	given (5 kw)	not known	not known	not known
(171)	Conventional Electricity	Survey-based synthetic data	given (4.7 kW)	Not given	Not given	not known
(172)	Conventional Electricity	Survey-based synthetic data	not known	Not given	Not given	Not given

Table 1.4 Details of Resources Used

Reference	Type of system		Types of Resources	Type of Back-up
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	Off-grid	Grid-connected	Both	Solar	Wind	Biomass	Biogas	Bio-diesel	Micro-Hydro	Hydro-kinetic	Battery	Fuel Cell	Diesel Generator	Pumped Hydro Storage
(1)	✓			✓	✓	✓			✓		✓			
(2)	✓			✓	✓	✓	✓		✓		✓			
(51)	✓			✓	✓	✓			✓		✓		✓	
(52)	✓			✓							✓			
(53)	✓			✓							✓		✓	
(54)	✓			✓	✓						✓		✓	
(55)		✓		✓	✓						✓			
(56)	✓			✓	✓						✓		✓	
(57)	✓			✓	✓						✓		✓	
(58)		✓		✓	✓	✓					✓		✓	
(59)		✓		✓		(Municipality)							✓	
(60)	✓			✓	✓						✓			
(61)	✓			✓								✓		
(62)	✓			✓							✓			
(63)	✓			✓	✓						✓			
(64)	✓			✓							✓			
(65)	✓			✓						✓	✓		✓	✓
(66)	✓			✓	✓				✓		✓		✓	
(67)			✓	✓		✓					✓		✓	
(68)	✓			✓	✓						✓	✓		
(69)	✓			✓			✓				✓			✓
(70)	✓			✓			✓				✓		✓	
(71)	✓			✓			✓				✓			
(72)	✓			✓	✓						✓		✓	✓
(73)	✓			✓							✓	✓		
(74)	✓			✓	✓						✓		✓	
(75)			✓	✓	✓	✓			✓		✓		✓	
(76)	✓			✓							✓			
(77)	✓			✓	✓		✓				✓		✓	
(78)	✓			✓	✓			✓	✓		✓		✓	
(79)			✓	✓	✓			✓			✓		✓	
(80)		✓		✓							✓			
(81)	✓			✓	✓	✓	✓				✓		✓	
(82)	✓		✓	✓		✓					✓		✓	
(83)	✓			✓	✓						✓		✓	
(84)			✓	✓	✓						✓		✓	
(85)			✓	✓							✓		✓	
(86)		✓		✓		✓					✓		✓	
(87)	✓		✓	✓							✓			
(88)	✓			✓	✓				✓		✓		✓	
(89)	✓			✓	✓						✓			
(90)		✓		✓	✓		✓				✓			
(91)		✓		✓	✓	✓					✓			
(92)	✓			✓	✓	✓					✓		✓	
(93)	✓			✓	✓	✓			✓		✓		✓	
(94)	✓			✓	✓	✓	✓			✓	✓		✓	

(145)	✓			✓	✓	✓	✓				✓		
(146)	✓			✓	✓	✓	✓			✓	✓		
(147)	✓			✓	✓	✓	✓			✓	✓		✓
(148)	✓			✓	✓	✓	✓			✓	✓		
(149)			✓	✓	✓	✓	✓			✓	✓		✓
(150)	✓			✓	✓	✓	✓			✓	✓		✓
(151)	✓			✓	✓	✓	✓			✓	✓		✓
(152)	✓			✓	✓	✓	✓			✓	✓		✓
(153)	✓			✓	✓	✓	✓			✓	✓	✓	
(154)	✓			✓	✓	✓	✓			✓	✓		
(155)	✓			✓	✓	✓	✓			✓	✓		
(156)	✓			✓	✓	✓	✓			✓	✓		✓
(157)	✓		✓		✓	✓	✓			✓	✓		✓
(158)	✓		✓		✓	✓	✓			✓	✓		✓
(159)	✓		✓		✓	✓	✓			✓	✓		✓
(160)	✓		✓		✓	✓	✓			✓	✓		✓
(161)	✓			✓	✓	✓	✓			✓	✓		✓
(162)	✓			✓	✓	✓	✓			✓	✓	✓	
(163)	✓			✓	✓	✓	✓			✓	✓		
(164)	✓			✓	✓	✓	✓			✓	✓		
(165)	✓			✓	✓	✓	✓			✓	✓		
(166)	✓			✓	✓	✓	✓			✓	✓		
(167)			✓	✓	✓	✓	✓			✓	✓		
(168)	✓			✓	✓	✓	✓			✓	✓		
(169)													
(170)	✓					✓				✓	✓		
(171)	✓			✓						✓	✓		
(172)	✓			✓	✓	✓	✓			✓	✓		✓

Table 1.5 Details of software and type of resource input data

Reference	Year of Publication	Name of software/technique used	Types Of Resources Data For							
			Solar	Wind	Biomass	Biogas	Bio-diesel	Micro-Hydro	Hydro-kinetic	
(1)	2015	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)				Synthetic (Survey-Based)	
(2)	2016	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)			Synthetic (Survey-Based)	
(51)	2022	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)						
(52)	2017	HOMER PRO	Synthetic (NASA)							
(53)	2021	HOMER PRO	Synthetic (NASA)							
(54)	2023	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)						
(55)	2021	Multi-objective mutation-based quantum-behaved particle swarm optimization (MOMQPSO)	Synthetic (NASA)	Synthetic (NASA)						
(56)	2022	HOMER PRO	Synthetic (NASA)							
(57)	2022	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)						
(58)	2022	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)					
(59)	2021	HOMER PRO, MATLAB	Synthetic (NASA)							
(59)	2021	Multi-Strategy Fusion Artificial Bee Colony (MFABC)	Real (Measured) data from other literature							
(60)	2016	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)						
(61)	2021	HOMER PRO	Synthetic (NASA)							

(63)	2015	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				
(64)	2023	HOMER PRO, RAMP	Synthetic (NASA)					
(65)	2018	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				Synthetic (Survey-Based)
(66)	2020	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				Synthetic (Survey-Based)
(67)	2017	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)			
(68)	2015	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				
(69)	2019	Moth Flame Optimization (MFO) and Water-Cycle Algorithm (WCA)	Real (Measured) data					Synthetic (Survey-Based)
(70)	2020	HOMER PRO	Real (Measured) data					Synthetic (Survey-Based)
(71)	2021	HOMER PRO	Real (Measured) data					Synthetic (Survey-Based)
(72)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				
(73)	2019	HOMER PRO	Real (Measured) data					
(74)	2023	MATLAB	Synthetic (NASA)	Synthetic (NASA)				
(75)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(76)	2023	HOMER PRO, RAMP	Synthetic (NASA)					
(77)	2021	Hybrid Particle Swarm Optimizer-Grey Wolf Optimizer (PSO-GWO)	Real (Measured) data	Real (Measured) data				Synthetic (Survey-Based)
(78)	2013	HOMER PRO (Hybrid Optimization of Multiple Energy Resources)	Synthetic (NASA)	Synthetic (NASA)			Synthetic (Survey-Based)	Synthetic (Survey-Based)
(79)	2018	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)			Synthetic (Survey-Based)	Synthetic (Survey-Based)
(80)	2017	HOMER PRO	Synthetic (NASA)					
(81)	2019	Particle Swarm Optimization, Gradient descent algorithm (GDA) with Multivariable linear regression analysis (MVLRL)	Real (Measured) data	Real (Measured) data	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(82)	2020	Particle Swarm Optimization (PSO)	Synthetic (NASA)		Synthetic (Survey-Based)			
(83)	2023	HOMER PRO, SIMA PRO	Synthetic (NASA)	Synthetic (NASA)				
(84)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				
(85)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				
(86)	2021	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)			
(87)	2019	HOMER PRO, MATLAB	Synthetic (NASA)					
(88)	2018	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				Synthetic (Survey-Based)
(89)	2013	HOMER PRO	Real (Measured) data	Real (Measured) data				
(90)	2022	HOMER PRO	Real (Measured) data	Real (Measured) data				Synthetic (Survey-Based)
(91)	2023	Gaining-sharing knowledge algorithm (GSK), HOMER PRO, Genetic algorithm (GA) and Biogeography-based optimization (BBO)	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			
(92)	2021	HOMER PRO	Real (Measured) data	Real (Measured) data	Synthetic (Survey-Based)			
(93)	2018	Particle Swarm Optimization (PSO) technique	Synthetic (NASA)					Synthetic (Survey-Based)
(94)	2017	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(95)	2023	HOMER PRO, MATLAB	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(96)	2020	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(97)	2016	Genetic Algorithm (GA)	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(98)	2016	HOMER PRO, GA, PSO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			Synthetic (Survey-Based)
(99)	2016	HOMER PRO, GA	Synthetic (Literature)	Synthetic (Literature)	Synthetic (Survey-based)			Synthetic (Survey-Based)
(100)	2020	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)				Synthetic (Survey-Based)
(101)	2020	HOMER PRO	Synthetic (Synergy)	Synthetic (NASA)				Synthetic (Survey-Based)
(102)	2014	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)			
(103)	2016	HOMER PRO	Synthetic (NASA)					
(104)	2017	Genetic algorithm (GA), Particle swarm Optimization (PSO), Butterfly Particle Swarm Optimization (BFPSO) and	Real (Indian Meteorological Department) data		Synthetic (Survey-Based)			

		Teaching-Learning-Based Optimization (TLBO) Optimization Techniques				
(105)	2016	HOMER, MATLAB and GAMBIT software	Synthetic (NASA)	Synthetic (NASA)		
(106)	2019	Firefly Algorithm (FA) in MATLAB	Synthetic (NASA)	Synthetic (NASA)		
(107)	2020	Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Grasshopper Optimization Algorithm (GOA), Grey Wolf Optimization (GWO), Salp Swarm Algorithm (SSA), Moth Flame Optimization (MFA), Dragonfly Algorithm (DA), Differential Evolutionary Algorithm (DEA), Ant Lion Optimization (ALO)	Synthetic (NASA)		Synthetic (Survey-Based)	
(108)	2020	GA, PSO, Numerical Optimization Algorithm (NUA), SSA	Synthetic (NASA)	Synthetic (NASA)		Synthetic (Survey-Based)
(109)	2023	HOMER, SIMA PRO 9	Synthetic (NASA)	Synthetic (NASA)		
(110)	2019	HOMER PRO, MATLAB	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	
(111)	2020	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		Synthetic (Survey-Based)
(112)	2017	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		
(113)	2022	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)	
(114)	2016	Artificial Bee Colony (ABC) Optimization	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	
(115)	2021	Artificial Bee Colony (ABC) Optimization, PSO in MATLAB	Synthetic (NASA)		Synthetic (Survey-Based)	
(116)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		Synthetic (Survey-Based)
(117)	2012	BBO, HOMER PRO	Real (Measured) data	Real (Measured) data		
(118)	2020	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(119)	2023	HOMER PRO, RAMP	Synthetic (NASA)			Synthetic (Survey-Based)
(120)	2010	HOMER PRO		Synthetic (NASA)		
(121)	2014	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		
(122)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		
(123)	2021	HOMER PRO	Synthetic (NASA)			
(123)	2021	HOMER PRO	Synthetic (NASA)			
(124)	2016	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		Synthetic (Survey-Based)
(125)	2022	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)	Synthetic (Survey-Based)
(126)	2009	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	
(127)	2019	PV Syst	Synthetic (NASA)			
(128)	2013	HOMER PRO	Not mentioned	Not mentioned	Synthetic (Survey-Based)	
(129)	2017	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(130)	2018	HOMER PRO	Real (Measured) data			
(131)	2023	MATLAB	Synthetic (PVGIS)			
(132)	2012	HOMER PRO	Synthetic (TREDA)		Synthetic (Survey-Based)	
(133)	2014	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		
(134)	2014	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)	
(135)	2019	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(136)	2021	Biogeography based Optimization (BBO) algorithm	Real (Measured) data	Real (Measured) data		
(137)	2019	Experimental Investigation	Real (Measured) data			
(138)	2012	HOMER PRO	Synthetic (Mathematical modelling)			
(139)	2017	HOMER PRO	Synthetic (NASA)			
(140)	2021	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		
(141)	2022	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)		
(142)	2022	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)	

(143)	2016	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)		
(147)	2022	Differential Evolution (DE), PSO (Particle Swarm Optimization), and GA (Genetic Algorithm) (MATLAB)	Synthetic (NASA)	Synthetic (NASA)			
(148)	2016	Discrete Harmony Search (DHS) Algorithm	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(149)	2023	MATLAB	Real (Measured) data	Real (Measured) data			
(150)	2016	HOMER PRO	Synthetic (NASA)		Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(150)	2016	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)	
(151)	2011	LINGO software and HOMER, Binary Search Optimization Technique for sizing PV in C++	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(152)	2015	Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Biogeography Based Optimization Techniques (BBO)	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(153)	2011	LINGO software and HOMER, Binary Search Optimization Technique for sizing PV in C++	Synthetic (NASA)				
(154)	2016	Cuckoo Search (CS) Algorithm in MATLAB	Synthetic (NASA)	Synthetic (NASA)			
(155)	2017	Cuckoo Search (CS) Algorithm in MATLAB	Synthetic (NASA)	Synthetic (NASA)			
(156)	2015	HOMER PRO, GA and PSO	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)		
(157)	2010	Mixed Integer Linear Programming in C++			Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(158)	2009	Mixed Integer Linear Programming in C++			Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(159)	2010	Mixed Integer Linear Programming in C++			Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(160)	2009	Mixed Integer Linear Programming in C++			Synthetic (Survey-Based)	Synthetic (Survey-Based)	Synthetic (Survey-Based)
(161)	2022	HOMER PRO	Synthetic (NASA)	Synthetic (NASA)			
(162)	2022	Differential Evolution (DE), HOMER PRO, PSO (Particle Swarm Optimization), and GA (Genetic Algorithm) (MATLAB)	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)		
(163)	2009	HOMER PRO	Synthetic (MNRE)				
(164)	2014	HOMER PRO	Synthetic (NASA)			Synthetic (Survey-Based)	
(165)	2022	Non-Dominated Sorting Genetic Algorithm II	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)		
(166)	2022	HOMER PRO	Synthetic (MNRE)		Synthetic (Survey-Based)		
(167)	2019	HOMER Pro, PSCAD and LABVIEW	Real (Measured) data	Real (Measured) data	Synthetic (Survey-Based)		
(168)	2017	HOMER PRO	Real (Measured) data				
(169)	2015	HOMER PRO					
(170)	2016	HOMER PRO			Synthetic (Survey-Based)		
(171)	2017	HOMER PRO	Synthetic (NASA)				
(172)	2009	LINGO software and HOMER, Binary Search Optimization Technique for sizing PV in C++	Synthetic (NASA)	Synthetic (NASA)	Synthetic (Survey-Based)	Synthetic (Survey-Based)	

also diversified into irrigation, electric space and water heating, hydrogen generation, sewage treatment, solar home lighting, reverse osmosis desalination. However, there are rarely any investigations which have considered electric cooking and electric transportation. The type of data required to generate the demand is mostly survey based synthetic data, assumption based synthetic data without any survey or real data. Assumption- based data are the mostly approximate or deviate from real data as they do not take any form of user behavior into account and do not involve any survey for appliance use while survey-based assumption does take the time of appliance use into account but generate non-stochastic data which can significantly vary from real or metered data. These deviations can broadly impact the eventual DES configuration in terms of performance and economic aspect (176–181). A few software and technique have been developed for generation of load data in close proximity of real data. About 20 % of the investigations have been conducted with assumption based synthetic data while 70 % have been conducted with survey based synthetic data and 10% have been conducted with real data. However, the newly developed software and techniques (176–181) have been rarely used in the investigations conducted in India where real load data is not available. The implications of load profile on the system output parameters can be comprehended by load profile parameters like load factor, peak demand, percentage day-to-day variations and percentage time-step variations. Though several literatures have mentioned the values of load factor and peak demand, but rarely have they tried to deduce any correlation between them and the system output parameters. The impact of variations of load demand on a timestep basis or day-to-day basis have barely been investigated before.

1.3.3 Resource Availability and backups

The most important parameter for DES modelling is resource availability. Resource availability in the form of solar irradiation potential, wind speed, hydrokinetic velocity, hydro flow rate, biomass potential, geothermal potential, tidal energy potential etc. are some of the most important input parameters for decentralized energy systems modelling. The biggest issue with renewable energy resources is their intermittency which greatly impact the capacity factor of the system and the overall configuration of the system. The resource potential can greatly vary from region to region from district level to country level and therefore can significantly impact the result as the best DES configuration for a particular location may not be the best one for another location simply due to the varying resource potential. The back-ups used for techno-economic investigations are battery, fuel cell, diesel generator, pumped hydro-storage etc. The details for the investigations of different resources and back-ups used for techno-economic in India are provided in **Table 1.4**. Almost 80% (96) of the investigations have considered off-grid systems while 13 investigations have considered grid connected systems while 17 investigations have considered both off-grid and grid-connected systems. Solar is the most common resource considered in almost all the investigations followed by wind. The least considered resources are biodiesel and hydrokinetic. On comparing back-ups, battery is the most commonly considered back-up while pumped hydro is the least considered. Apart from the infrastructural requirements, the relative newness of pumped hydro concept is one the reasons behind this situation. Very few literatures have considered more than two renewable energy sources in their investigations.

1.3.4 Details of techniques, software and resource data used for investigations

The various techniques used for conducting the investigations are provided in **Table 1.5** along with the year of publication. HOMER PRO is the most prominent software used for these investigations covering almost 55 % of the investigation. The prime reason for this is due to the software being a dedicated software for this purpose only, its user friendliness and its vast coverage of resources. Several meta heuristic optimization techniques have been used for these investigations. These include Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC) Optimization, Discrete Harmony Search (DHS) Optimization, Moth Flame Optimization (MFO), Water-Cycle Algorithm (WCA) optimization, Biogeography Based Optimization (BBO), Genetic algorithm (GA), Grasshopper Optimization Algorithm (GOA), Grey Wolf Optimization (GWO), Salp Swarm Algorithm (SSA), Moth Flame Optimization (MFA), Dragonfly Algorithm (DA), Differential Evolutionary Algorithm (DEA), Ant Lion Optimization (ALO), Gradient descent algorithm (GDA), Butterfly Particle Swarm Optimization (BFPSO), Firefly Algorithm (FA), Multi-Strategy Fusion Artificial Bee Colony (MFABC), Numerical Optimization Algorithm (NUA), Hybrid Particle Swarm Optimizer-Grey Wolf Optimizer (PSO-GWO),

Multi-Objective Mutation-Based Quantum-Behaved Particle Swarm Optimization (MOMQPSO), Non-Dominated Sorting Genetic Algorithm II and Teaching-Learning-Based Optimization (TLBO) Optimization Techniques. Many of these algorithm formulations have been developed in MATLAB and C++, while many literatures have not disclosed the software. Few literatures have also used Mixed Integer Linear Programming (MILP) developed in MATLAB, C++ and a software developed for solving MILP problems named LINGO also has been used. (130) has used PV Syst for conducting the investigation while (182) has solely conducted experimental investigation. For resource data more than 107 (85%) of the articles have used synthetic data for measuring solar and wind energy resources while the data for other resources namely biomass, biogas, hydro, hydrokinetic, biodiesel are synthetic only based on surveys and literatures (**Table 1.5**). The majority of the solar radiation and wind speed data have been obtained from NASA or NREL database used in HOMER PRO while 18 articles have used measured or real data for both solar and wind energy resources (**Table 1.5**).

1.3.5 Details of Sources for Technical and Economic Parameters, Constraints and Sensitivity Parameters

The details of sources for technical and economic parameters along with constraints and sensitivity parameters are provided in **Table 1.6**.

Technical specifications and economic parameters of different components play an important role in these investigations as they can significantly impact the output parameters in terms of costs and performances. The main technical parameters include the specific capacities of each component to be considered, their specified efficiency parameters etc. while the economic parameters include the capital costs, the replacement costs, the operation and maintenance costs. These parameters may be assumed, can be based on previously conducted literature works and directly based on physical or online surveys of markets via quotation calls. Sometimes real data may also exist if a specific component has been already purchased and installed. The assumption-based parameters are likely to give the most inaccurate results as these may significantly vary from real data. The real data will give the most accurate results, though it's the most difficult to acquire as most of these investigations are conducted prior to installation of a real system to check its feasibility. The literature-based data may provide reasonable results in close proximity of real data if they have been taken from a recently published literature, but may provide deviated results if taken from very old literatures since the technical specifications and economic parameters change very frequently with time. A survey-based data on prevailing market specifications and prices is likely to provide the more accurate results in close proximity of real results. (92) has used real data for technical specifications and capital costs. Approximately (25 articles) 20 % of the articles have conducted market and literature surveys. About (50 articles) 40 % of the articles have used literature-based data for both technical and economic parameters while (49 articles) 40% have used assumption-based data. Few research articles have used technical specifications of manufacturers available in the HOMER PRO database which are reasonably accurate. However, many of these manufacturers are unlikely to be available in Indian market and may have a very high capital costs when compared to the manufacturers available in India and use of such data may over-estimate the performance and economic parameters of the system.

Constraints are input parameters which act as limits for the investigation. They provide upper and lower limits on the range of input parameters which are not definitive in nature and may change with time and are specific to the location of study. The constraints considered in literatures are minimum and maximum capacity shortage, interest rate, discount rate, project lifetime, grid penetration limit, capacity shortage, maximum renewable energy penetration, maximum capacity of system components, time constrained grid availability, time constrained availability of renewable energy generators, minimum renewable fraction, battery minimum and maximum state of charge, operating reserve of system components.

When real data for a particular input parameter is not available and the obtained results may likely deviate from real results or when a particular investigation may need to provide a broader perspective over a much larger region with varying input parameters starting from resource availability, technical and economic specifications, then sensitivity analysis is conducted. Sensitivity analysis involves changing a particular value of an input parameter and comprehending its impact on the

outcome which may lead to some conclusions or theory. The various sensitivity parameters used in literatures are, Hydrokinetic Flow Rate, Wind Speed, Solar Radiation, Capacity Shortage, Fuel Price, Capital Cost of System Components, Number of Batteries, Daily Energy Demand, Peak Load, Loss of Load Probability (LOLP) values, The Weights of Criteria/Parameters used for Determination of The Best Battery, Schedule Of Biomass and Biogas Generator, Discount Rate, Unmet Load, Battery Damage Rate, Annual Interest Rate, Discount Rates, Inflation Rate, Component Lifetime, Project Duration Years, PV Derating Factors, Biomass Collection Rate, Biomass Quantity, Battery Round-Trip Efficiency, Hydrogen Tank Size, Grid Electricity Rate, Demand For EV Charging Stations, Internal Rate of Return (IRR), Weightages Of Systems In MCDM Technique, PV Outage, Computational Parameters (Max Iterations-Population Size-Search Space Reduction Factor-Number of Best Solutions to Calculate Mind Point), Inertia Weight-Acceleration Loss of Power Supply Probability (LPSP), Coefficient-Iteration, Project Lifetime, Biomass Gasification Ratio, Inverter Efficiencies, Renewable Energy Fraction, , Daily Ambient Temperature.

1.3.6 Details of Technical and Economic Output Parameters

The output parameters help us to identify the optimized configuration of the system that will supply the energy demand at minimum costs and also realize the feasibility of the system in terms of costs, reliability and competitiveness with the existing systems that is generally grid. The details of the various technical and economic output parameters are provided in **Table 1.7**. These are total net present cost (TNPC) or net present cost (NPC), levelized cost of energy (LCOE), capacity shortage, internal rate of return (IRR), excess electricity, renewable fraction, unmet load, break up of total annualized costs (capital costs, operation and maintenance costs, fuel costs, salvage value), optimal component capacities, area requirement, emissions, breakdown of individual component production, comparison with grid extension, employment potential, payback period, grid purchase, grid sales etc.

The highest literatures investigated for LCOE (123 literatures) and NPC (120 literatures), optimal component capacities (90 literatures). Few investigations have investigated beyond technical parameters namely emissions, employment potential, human development index, human performance index, human health damage, comparison with and without Demand Side Management (DSM), Energy Index Ratio (EIR), Local Transportation.

Few literatures have compared the metaheuristic processes used for conducting the investigations.

1.4 Identified Research Gaps

Several research gaps have been identified based on the literature reviews conducted for India and overall literature reviews conducted worldwide.

- Only superficial investigations have been conducted for Sikkim considering the entire state as a single climate region. No deep work has been conducted for Sikkim involving dedicated location/region-based or application-based analysis and involving single or multiple energy resources prior to this research work.
- The constraints considered in literatures have not considered area requirement for the system as a constraint or any additional costs required for purchase of land or area for installations.
- There is a possibility to use software like RAMP for modelling demand data when real time series data is not available.
- Very few literatures have investigated the impact of change of load profiles on the system performance and economic parameters.
- Very few literatures which have investigated the impact of electric cooking addition on conventional electric load.
- Very few investigations have considered the impact of grid unreliability on the system performance and economic parameters.

Table 1.6 Details of Sources for Technical and Economic Parameters, Constraints and Sensitivity Parameters

Reference	Sources of Technical and Economic Input Parameter		Constraints	Sensitivity Parameters
	Technical Parameters	Economic Parameters		
(1)	Literature And Assumption Based	Literature And Assumption Based	Capacity Shortage-Maximum Capacity Of Biomass And Micro Hydro Power Plant-Schedule Of Biomass Generator	-
(2)	Literature And Market Survey Based	Literature And Market Survey Based	Capacity Shortage	Electrical Demand-Mean Annual Wind Speed-Maximum Annual Capacity Shortage - Biomass Price.
(51)	Literature Based	Literature Based	Capacity Shortage	Inflation Rate-Nominal Discount Rate-Diesel Fuel Price-Solar Radiation-Wind Speed-Electric Demand-Component Capital Costs
(52)	Literature Based	Literature Based	Project Lifetime	Solar Radiation-Electric Demand- Electricity Rate-Annual Capacity Shortage.
(53)	Literature Based	Literature Based	-	-
(54)	Literature Based	Literature Based	-	Discount Rates-Diesel Fuel Prices
(55)	Assumption Based	Assumption Based	Maximum And Minimum Withdrawable Grid Power	Battery Damage Rate-Electrical Demand-Capital Cost Of Battery and PV-Grid Capacity
(56)	Assumption Based	Assumption Based	-	Capital Cost of System Components
(57)	Literature And Market Survey Based	Literature And Market Survey Based	Maximum Yearly Storage Capacity-Minimum Renewable Fraction-Load Demand In Current Time Step-Annual Full Load-PV Power Output Wind Turbine Output Power.	Project Duration Years-Yearly Average Load Demand-PV Derating Factors
(58)	Survey Based	Literature Based	-	Components Cost- Internal Rate of Return (IRR)
(59)	Survey And Assumption Based	Literature Based	Carbon Emissions-Reliability-Renewable Fraction-Battery Constraints	Round Trip Efficiency
(59)	Assumption Based	Assumption Based	Economic Criteria-Power Balance Criteria-Power Output Limit-Battery Constraints	-
(60)	Assumption Based (HOMER PRO Directory)	Assumption Based (HOMER PRO Directory)	-	-
(61)	Literature Based	Literature Based	-	-
(62)	Literature Based	Literature Based	Constrained System Capacity-Real Interest Rate.	-
(63)	Assumption Based	Literature Based	Project Lifetime-Constrained System Capacity	-
(64)	Literature And Survey Based	Literature and Survey Based	Interest Rate-Inflation Rate-Annual Capacity Shortage-Project Lifetime	Depth Of Discharge (DOD) Of Batteries-Battery Life-Battery Throughput-Daily Solar Radiation-Daily Ambient Temperature-Average Household Urban Plinth Area-Effective Roof Utilization Factor-Household Monthly Load Demand
(65)	Literature And Market Survey Based	Literature And Market Survey Based	-	-
(66)	Literature Based	Literature Based	Project Lifetime-Minimum. Renewable Penetration-Penalty Cost for Carbon Emission	Hydro Flow Rate-Discount Rate-Wind Speed
(67)	Assumption Based	Literature Based	Unreliable Grid	Biomass Price-Diesel Price-Global Capital Cost of Solar Radiation-Photovoltaic System, Biomass Gasification System and Diesel Generator.
(68)	Assumption Based	Assumption Based	-	Daily Energy Demand-Peak Load
(69)	Literature And Survey Based	Literature And Survey Based	-	Loss of Load Probability
(70)	Literature Based	Literature Based	Project Lifetime-Capacity Shortage-Discount Rate-Inflation Rate	The Weights of Criteria/Parameters used for Determination of The Best Battery
(71)	Literature Based	Literature Based	Operating Reserve-Battery Minimum State of Charge-Project Life Time-Discount Rate-Inflation Rate.	Energy Demand-Peak Load-Capacity Shortage Fraction.
(72)	Literature Based	Literature Based	-	-
(73)	Market And Survey Based	Literature Based	Discount Rate-Inflation Rate-Link Turbidity Factor- Capacity Shortage	Capacity Shortage
(74)	Literature Based	Literature Based	LPSP-System Capacity	Inertia Weight-Acceleration Coefficient-Iteration-Project Lifetime,
(75)	Literature Based	Literature Based	-	-
(76)	Literature And Survey Based	Literature and Survey Based	-	-
(77)	Literature Based	Literature Based	-	Battery Round-Trip Efficiency
(78)	Literature And Market Survey Based	Literature And Market Survey Based	-	Bio-Diesel Price-Hydrokinetic Flow Rate-Wind Speed
(79)	Literature Based	Survey Based	-	-
(80)	Literature Based	Market and Literature Based	-	PV Penetration-Battery Capacity-PV Capacity
(81)	Literature Based	Literature Based	-	Solar Radiation-Wind Speed-Capital Cost of System Components
(82)	Literature And Assumption Based	Survey and Assumption Based	None	Diesel Fuel Price-Biomass Fuel Price-Interest Rate-Capital Cost of System Components.
(83)	Literature Based	Literature Based	-	Solar Radiation-Fuel Price-Load Variation
(84)	Literature Based	Assumption Based	LPSP- Number of Wind Turbines	Capital Cost Of Components-Nominal Discount Rates-Inflation Rate-Diesel Fuel Price
(85)	Literature Based	Literature Based	-	None
(86)	Literature Based	Literature Based	-	Energy Demand-Wind Generation System-PV Generation System and Diesel Generation Units
(87)	Literature And Survey Based	Literature And Survey Based	-	Wind Speed-Solar Radiation-Load Demand
(88)	Assumption Based	Assumption Based	-	-

(89)	Real Data	Real Data And Assumption Based	Capacity Shortage	Capacity Shortage
(90)	Literature And Market Survey Based	Literature And Market Survey Based	Project Life Time-Interest Rate	Real Interest Rate-Solar Radiation-Capacity Shortage-Biomass Gasifier Lifetime
(91)	Assumption Based	Survey Based	Renewable Fraction-Dispatch strategy	Fuel Cost-Discount Rate-Battery Cost-DG Cost-PV Cost
(92)	Literature Based	Literature Based	-	Solar Radiation-Fuel Price-Demand Variation
(93)	Assumption Based	Assumption Based	-	Inflation Rate-Discount Rate-Capital Cost Of PV and Battery
(94)	Literature And Survey Based	Literature And Survey Based	-	Biomass Price-Wind Speed
(95)	Literature Based	Literature Based	Discount Rate-Inflation Rate-Capital Cost-Operation and Maintenance Cost-Replacement Cost.	Weightages Of Systems In MCDM Technique
(96)	Assumption Based	Assumption Based	Project life-Interest Rate	-
(97)	Literature Based	Literature Based	Project Life Time-Discount Rate-Inflation Rate	Schedule Of Biomass and Biogas Generator
(98)	Literature Based	Literature Based	-	-
(99)	Literature Based	Literature Based	Spinning Reserve-Minimum Renewable Fraction-Annual Interest Rate- Project Lifetime	-
(100)	Assumption Based	Assumption Based	Reliability Criteria And Battery State of Charge	Fuel Cost-PV Cost-Battery Cost-Load Demand
(101)	Literature Based	Literature Based	-	Discount Rate-PV Cost-Battery Cost-Fuel Cost-Wind Speed-Designed Flow Rate
(102)	Assumption Based	Assumption Based	Equipment Operating Range (Minimum and Maximum Loading)-Starting and Shutdown Time of the Generators-Life and Outage of The Equipment Percentage Peak Load-Percentage Output Power of Different Renewable Energy Sources-Energy Saving of Grid Electricity-Reduction of Emission Factors.	Tariff Rate-Capital Cost of PV-Wind Velocity
(103)	Literature Based	Literature Based	-	-
(104)	Literature Based	Literature Based	-	Solar Radiation-Biomass Fuel Price-Discount Rate.
(105)	Assumption Based	Assumption Based	-	Hydrogen Tank Size
(106)	Literature And Assumption Based	Literature and Assumption Based.	-	Diesel Price-Annual Interest Rate
(107)	Literature And Market Survey Based	Literature and Market Survey Based	Constrained Schedule of Biomass Generator-LPSP	Interest Rate-Biomass Collection Rate-Cost of Biomass
(108)	Literature Based	Assumption Based	-	Interest Rate-Diesel Prices
(109)	Literature Based	Literature Based	-	-
(110)	Literature Based	Literature Based	Power Balance-Battery Constraints-Power Generating	Demand For EV Charging Stations, Load Demand, Absence Of Wtb Plant, Cumulative Effect Of The Three
(111)	Literature Based	Literature Based	-	Solar Radiation- Daily Biomass Supply
(112)	Assumption Based	Assumption Based	-	-
(113)	Survey And Assumption Based	Survey And Assumption Based	Interest Rate-Inflation Rate-Capacity Shortage-Project Lifetime	Discount Rates-Inflation Rate
(114)	Literature Based	Literature Based.	Battery State of Charge-Maximum Number of Batteries and Panels.	Solar Radiation-Biomass Quantity
(115)	Literature Based	Assumption Based	-	-
(116)	Assumption Based	Assumption Based	-	Global Solar Irradiation -Annual Wind Speed.
(117)	Assumption Based	Assumption Based	-	-
(118)	Literature And Survey Based	Literature and Survey Based	Interest Rate-Inflation Rate-Annual Capacity Shortage-Project Lifetime-Maximum Capacity Of System Component	River Flow Speed-Capital Costs of Hydrokinetic Turbines-Interest Rates-Inflation Rates-Load Demand.
(119)	Literature And Survey Based	Literature and Survey Based	-	-
(120)	Assumption Based	Assumption Based	-	Wind Speed
(121)	Assumption Based	Assumption Based	-	-
(122)	Literature Based	Literature Based	-	Diesel Fuel Cost-Intermittent Solar Radiation and Wind Speed-Nominal Discount Rate-Scaled Daily Average Demand
(123)	Assumption Based (HOMER PRO)	Assumption Based (HOMER PRO)	Maximum Annual Capacity Shortage-Minimum Renewable Fraction, Generation of Electricity \geq Consumption Load. Nominal Discount Rate-Expected Inflation Rate-Real Discount Rate-Project Lifetime	Diesel Price-Solar Radiation
(123)	Survey And Assumption Based	Literature Based.	-	PV Outage-Component Cost-Computational Parameters (Max Iterations-Population Size-Search Space Reducton Factor-No Of Best Solutions To Calculate Mind Point)
(124)	Assumption Based (HOMER PRO)	Assumption Based	-	-
(125)	Assumption Based	Literature Based	Maximum Annual Capacity Shortage-Minimum Renewable Fraction-Operating Reserve-Load in Current Time Step-Annual Peak Load-Maximum Solar and Wind Power Outputs-System Lifespan -Discount Rate-Inflation Rate.	-
(126)	Assumption Based	Assumption Based	-	Wind Speed-Solar Radiation
(127)	Literature Based	Assumption Based	-	-
(128)	Assumption Based	Assumption Based	-	-

(129)	Literature Based	Literature Based	Annual Interest Rate-Project Duration-Electrical Operating Reserve	Electrical Energy Demand-Cost of Biomass-Diesel price
(130)	Literature Based	Literature Based	Optimization Power Factor	Inverter Efficiencies-PV Derating Factor.
(131)	Literature Based	Literature Based	RE Self Utilization Fraction-Probability of Grid Power Absorption-Power Balance Constraint-Frequency Of Reservoir Utilization	Cost of Components-Nominal Discount Rates-Inflation Rate-Diesel Fuel Price
(132)	Assumption Based	Assumption Based	-	-
(133)	Literature And Assumption Based	Literature And Assumption Based	Grid Penetration	-
(134)	Literature Based	Literature Based	Annual Real Interest Rate-Project Lifetime-Maximum Annual Capacity Shortage	Solar Radiation-Wind Speed-Capital Cost Of PV And Wind System
(135)	Assumption Based	Assumption Based	Time Constrained Grid Availability	-
(136)	Survey And Assumption Based	Survey And Assumption Based	Power Reliability-Carbon Emission-Renewable Energy Fraction	-
(137)	Literature Based	Literature Based.	-	Wind Speed-Solar Radiation-Capital Cost
(138)	Assumption Based	Assumption Based	Loss of Load Probability (LLP)-System Autonomy (SA)-Battery State of Charge	-
(139)	Literature And Survey Based	Literature and Survey Based	Project Lifetime- Real Interest Rate	-
(140)	Literature Based	Literature Based	-	Different Algorithms Were Used
(141)	Literature And Survey Based	Literature and Survey Based	Unknown	Capital Cost-LPSP
(142)	Assumption Based	Assumption Based	Biomass Price	Load Demand-Solar Radiation-Biomass-Price-Annual Capacity Shortage-Interest Rate-Biomass Gasifier Life-Gasification Ratio-PV Lifetime-PV Derating Factor
(143)	Literature Based	Literature Based	-	Discount Rate-Solar Radiation-Interest Rate-Diesel Price
(145)	Literature And Assumption Based	Literature And Assumption Based	Constraints on Battery SOC-Area Availability for System Installation-Power Reliability	Unmet Load
(146)	Literature Based	Literature Based	-	Biogas Price- PV Capital Costs-Interest Rate-System Component Size-Electric Demand
(147)	Assumption Based	Assumption And Literature Based	-	Interest Rates-Fuel Cost-Capital Cost of Energy Source
(148)	Literature Based	Literature Based	Project Lifetime-Annual Real Interest Rate-Power Reliability-LPSP (Loss of Power Supply Probability)	-
(149)	Literature Based	Literature Based	Maximum Number of Components-Battery Charging Limit-	Inertia Weight-Acceleration Coefficient-Iteration-Project Lifetime-Interest Rate,
(150)	Assumption Based	Assumption Based	-	Diesel Price-Annual Interest Rate
(150)	Survey And Assumption Based	Literature Based	-	Biomass Fuel Price
(151)	Survey And Assumption Based	Survey And Assumption Based	-	-
(152)	Survey And Assumption Based	Survey and Assumption Based	EIR (Energy Index Ratio)-Limited Operating Hours of Biogas and Biomass Generator	-
(153)	Survey And Assumption Based	Survey and Assumption Based	-	Diesel Price-Discount Rate
(154)	Literature And Assumption Based	Literature Based	-	Different Values of LOLP (Loss Of Load Probability)
(155)	Market -Survey Based	Literature Based	-	PV Derating Factor-Capital Costs of System Components-Loss of power supply probability (LPSP).
(156)	Assumption Based	Assumption Based	Energy Index Ratio-Maximum Capacities of System Components	Renewable Energy Fraction
(157-160)	Survey And Assumption Based	Survey and Assumption Based	Steady Hourly Load-Battery SOC-Diesel Generator Constrained Schedule and Constrained Capacity Operation	-
(161)	Assumption Based	Assumption Based	-	-
(162)	Literature Based	Literature Based	-	-
(163)	Literature Based	Literature Based	-	Solar Radiation
(164)	Literature And Market Survey Based	Literature And Market Survey Based	Loss Of Load Probability (LOLP)/ Capacity Shortage	Loss Of Load Probability-Capacity Shortage
(165)	Literature Based	Literature Based	Loss Of Power Supply Probability (LPSP)-Hydrogen Storage Constraint	-
(166)	Assumption Based	Assumption Based	-	-
(167)	Survey, Literature And Assumption Based	Survey And Assumption Based	-	None
(168)	Assumption Based	Literature Based	-	Number of Batteries
(169)	Literature Based	Literature Based	Capacity Shortage- Interest Rate	Biomass Price-Capital Cost of Wind Turbine and Battery
(170)	Assumption Based	Assumption Based	-	Biomass Fuel Price
(171)	Literature Based	Literature And Assumption Based	Project Lifetime	-
(172)	Assumption Based	Assumption Based	Annual Interest Rate	Biomass Fuel Costs

Table 1.7 Details of Technical and Economic Output Parameters

Reference	Type of Output Parameter
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	NPC	LCOE	Capacity Shortage	Internal Rate of Return	Excess Electricity	Renewable Fraction	Unmet Load	Break up of Total Annualized Costs	Optimal Component Capacities	Area Requirement	Emissions	Employment Potential	Payback Period	Breakdown of individual component production	Other Aspects	Comparison with grid extension
(1)	✓	✓							✓	✓				✓		
(2)	✓	✓							✓			✓				
(51)	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓		✓	Human Performance Index, Human Development Index Comparison for 29 different locations	
(52)	✓	✓		✓		✓			✓				✓			
(53)			✓						✓					✓		
(54)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	Return on Investment, Human Development Index, Local Transportation Employment Comparison of optimization techniques	
(55)		✓					✓	✓			✓					
(56)	✓	✓			✓		✓	✓	✓		✓			✓		
(57)	✓	✓	✓		✓	✓	✓	✓	✓					✓		
(58)		✓		✓				✓			✓				Grid Purchase, Grid Sales	
(59)	✓	✓			✓			✓ (Capital, Replacement, Maintenance and Salvage Costs)	✓					✓		
(59)	✓	✓									✓					✓
(60)	✓	✓						✓	✓						Most feasible location (state)	
(61)	✓	✓						✓	✓					✓	Capacity Factor, Comparison among locations/ states	
(62)		✓						✓						✓	Grid Purchase, Grid Sales, Reliability and Environmental Analysis	
(63)	✓	✓	✓			✓								✓		
(64)	✓	✓	✓		✓	✓			✓	✓						✓
(65)	✓	✓				✓		✓	✓					✓		
(66)	✓	✓				✓					✓			✓	Reserved Capacity	
(67)	✓	✓	✓		✓		✓							✓	Grid Purchase, Grid Sales	✓
(68)	✓	✓			✓		✓		✓							
(69)	✓	✓			✓				✓	✓						
(70)	✓	✓					✓		✓					✓	Comparison of different back-up devices	
(71)	✓	✓	✓											(Battery) ✓		
(72)	✓	✓				✓					✓					
(73)	✓	✓		✓	✓	✓		✓	✓							
(74)	✓	✓			✓				✓	✓	✓			✓	Loss of Power Supply Probability	
(75)	✓	✓			✓				✓	✓	✓	✓		✓		✓

(76)	✓	✓					✓ (Capital, Replacement, Operation and Maintenance, Fuel and Salvage Costs)	✓					
(77)		✓			✓			✓				✓	
(78)	✓	✓	✓					✓		✓		✓	✓
(79)	✓	✓			✓		✓ (Capital, Replacement, Operation and Maintenance, Fuel and Salvage Costs)	✓		✓			✓
(80)	✓	✓			✓		✓					✓	
(81)												✓	Life Cycle Costs, Capacity Factor
(82)		✓	✓		✓		✓	✓		✓		✓	Comparison between HOMER and PSO
(83)	✓	✓			✓		✓					✓	
(84)	✓	✓								✓	✓	✓	
(86)	✓	✓					✓			✓		✓	
(87)	✓	✓				✓	✓	✓		✓		✓	Wind Speed
(88)	✓	✓			✓		✓	✓				✓	
(89)	✓	✓	✓				✓	✓				✓	
(90)	✓	✓			✓		✓	✓				✓	Grid Purchase, Grid Sales, Biogas Operation Hours
(91)	✓	✓			✓			✓		✓		✓	Grid Purchase, Grid Sales, Interest Rate, Biomass Price
(92)	✓	✓	✓		✓		✓ (Operating and Initial Cost)	✓		✓			
(93)	✓	✓			✓		✓	✓		✓		✓	
(94)	✓	✓					✓	✓				✓	
(95)	✓	✓			✓	✓	✓	✓				✓	
(96)	✓	✓		✓			✓	✓		✓		✓	Return on Investment
(97)	✓	✓	✓		✓			✓			✓	✓	
(98)	✓	✓			✓	✓		✓	✓			✓	
(99)	✓	✓			✓	✓		✓		✓		✓	
(100)	✓	✓						✓		✓			Comparison of different Demand Side Management Strategies
(101)	✓	✓			✓		✓ (Capital, Replacement, Operation and Maintenance, Fuel and Salvage Costs)	✓		✓			
(102)	✓	✓	✓		✓		✓ (Capital, Replacement, Operation and Maintenance, Fuel and Salvage Costs)	✓		✓		✓	✓
(103)	✓	✓								✓			
(104)		✓						✓		✓		✓	Comparison of different metaheuristic algorithms
(105)	✓	✓			✓		✓					✓	

(132)	✓	✓		✓			Maintenance, Replacement Cost)		✓			
(133)	✓	✓	✓				✓	✓				
(134)	✓	✓				✓	✓				✓	Grid Purchase, Grid Sales, Reliability and Environmental Analysis
(135)	✓	✓		✓	✓		✓	✓				
(136)	✓	✓			✓			✓				Energy Index Ratio, Diesel Fuel Consumption and Battery Consumption hours
(137)	✓	✓						✓			✓	Grid Purchase, Grid Sales
(138)					✓			✓	✓			
(139)	✓	✓	✓	✓				✓				
(140)	✓	✓			✓		✓	✓				
(141)	✓	✓		✓	✓	✓	✓ (Capital, Replacement, Operation and Maintenance, Fuel and Salvage Costs)	✓		✓	✓	Human Development Index
(142)	✓	✓	✓	✓	✓	✓	✓ (Operating and Initial Cost)	✓			✓	Capacity Factor
(143)	✓	✓										
(145)		✓					✓	✓	✓		✓	Comparison of micro wind turbines
(146)	✓	✓	✓				✓	✓				
(147)	✓	✓			✓	✓		✓		✓		
(148)	✓	✓				✓	✓	✓				
(149)	✓	✓										Time Elapsed in Optimization Process
(150)	✓	✓			✓		✓	✓		✓		Fuel Consumption
(150)	✓	✓			✓			✓		✓		
(151)	✓	✓						✓				
(152)	✓	✓		✓	✓			✓		✓	✓	Comparison of Dispatch Strategies
(153)		✓						✓				
(154)	✓	✓	✓		✓			✓		✓		
(155)	✓	✓	✓					✓				
(156)	✓	✓			✓			✓		✓		Energy Index Ratio, Total Fuel Consumed
(157–160)		✓				✓	✓				✓	Comparison of different batteries and metaheuristic algorithms
(161)	✓	✓			✓			✓		✓	✓	Grid Purchase, Grid Sales
(162)	✓	✓			✓		✓	✓		✓	✓	Comparison of different metaheuristic algorithms
(163)	✓	✓					✓ (Operating Costs)	✓				
(164)	✓	✓					✓ (Capital Costs)	✓				
(165)	✓	✓		✓				✓		✓	✓	Human Health Damage, Human Development Index, Capacity Factor

(166)	✓	✓		✓		✓		✓		✓		Return on Investment
(167)				✓		(Operating Costs)				✓	✓	Revenue from microgrid, net profit, net cumulative realization
(168)	✓	✓	✓		✓			✓				
(169)	✓	✓						✓				Comparison between DSM and without DSM
(170)	✓	✓	✓		✓		✓					✓
(171)	✓	✓					✓					✓
(172)	✓	✓										Energy Index Ratio

- There is a possibility to identify the best system not only on the basis of economic and technical parameters but also on the basis of other parameters like area requirement, emission analysis and employment potential etc.

1.5 Objectives of the present work

Based on the identified research gaps and motivation, the objectives of the present work are:

- To investigate the techno-economic-space feasibility of DESs for different types of load demand namely residential sector, school sector, market sector and small township comprising of all these sectors in the form of case-studies with the main emphasis on power outage ridden North-East Indian state of Sikkim and nearby North Eastern states.
- To identify the best resource or combination of renewable energy resources which are best suited for a particular location for a particular type of end-user considering various criteria which include costs, area requirement, renewable energy penetration, employability and green-house gas emissions.
- To understand the consequences of different types of user demand profile on the system configurations.
- To understand the consequence of sudden changes in demand profile on the system configuration in terms of economic and space feasibility.
- To analyze and compare the techno-economic performance of off-grid, grid-connected and grid-connected with battery systems.
- To attain a broader comprehension of these investigations with sensitivity analysis for critical uncertain parameters varying across the country of India.

Chapter 2 Methodology

A number of detailed investigations have been conducted in the form of case studies for a specific location of Sikkim which have been mainly governed by the type of load demand. A flowchart of the base methodology used for each of these investigations has been provided in **Figure 2.1**. The details of methodology have been discussed in the following sub-sections.

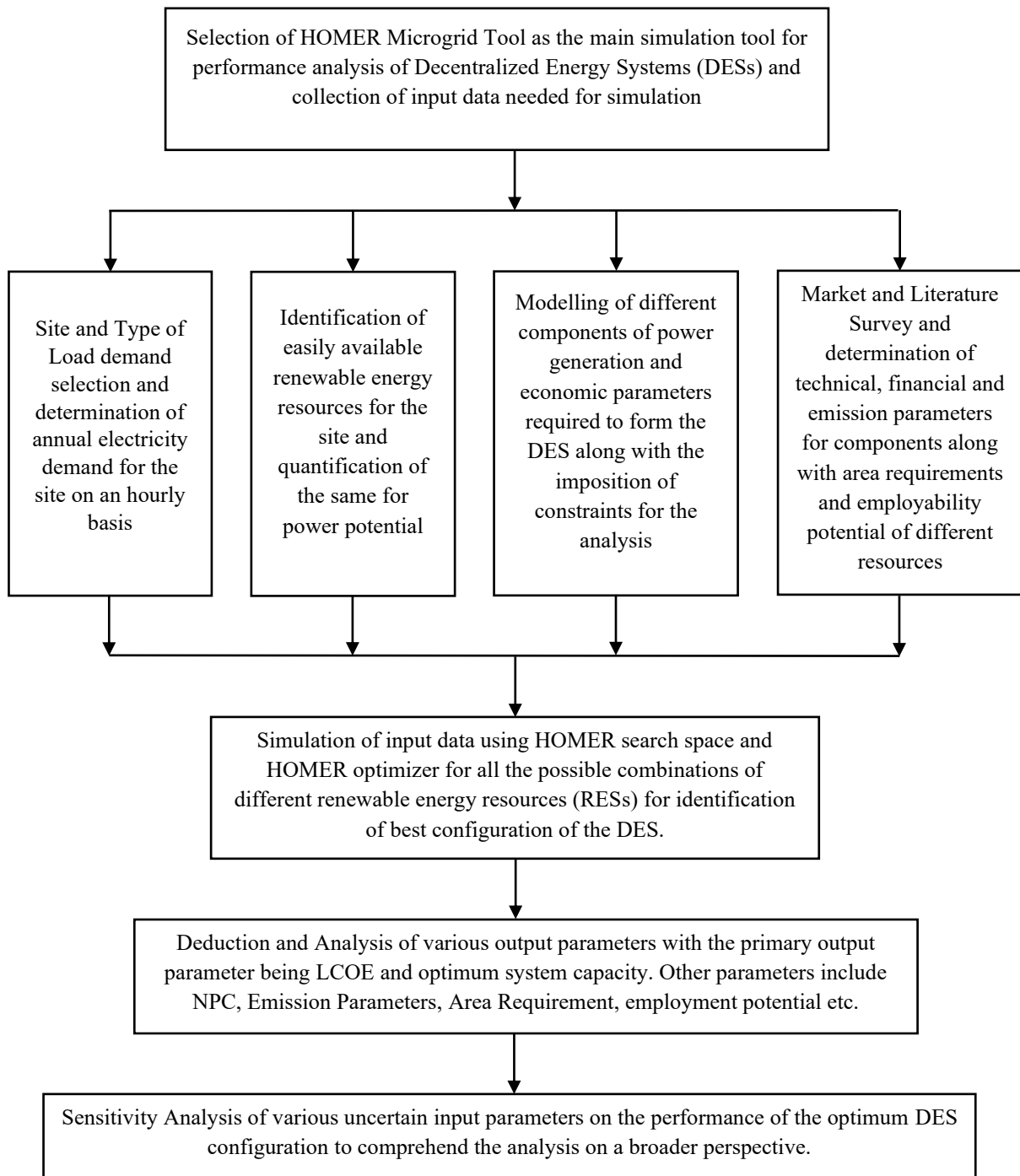


Figure 2.1 Methodology for the present analysis

However, each of these case studies have few modifications on the base methodology, unique to the case, by either supplementation with few additional steps of methodology or removal of steps from the base methodology which are discussed separately in the case study chapters.

2.1 Selection of Simulation Tool

HOMER Pro Microgrid Analysis Tool has been used as the primary simulation tool for conducting the techno-economic investigations of the decentralized energy system (DES) based on its popularity and robustness (50,183–185). HOMER pro has two optimization algorithms. These are HOMER Search Space and HOMER optimizer. The HOMER search space uses grid search algorithm while the “HOMER optimizer uses proprietary derivative-free algorithm for simulation” of all feasible system configurations to search for the least costly system respectively (183). The various inputs required for HOMER Pro have been discussed in the following sub-sections.

2.2 Selection of Location

For this analysis, Rangpo town under Pakyong district (previously East Sikkim) of Sikkim, India has been selected (**Figure 2.2**). The location has a highly cosmopolitan population comprising of a diverse appliance user base representative of a typical urban population in a very small population fraction.

This town has five suburban wards (186) with a population of 10540 and 2505 households as per census of 2011 (187). However, actual residing population may vary considerably as the census considers permanent residence instead of temporary residence and the population have increased significantly over the past decade due to influx of population from other States and other locations of Sikkim. The population comprises of local Sikkim inhabitants from different parts, immigrant industrial employees from other states of India, traders from Sikkim and other states, private residential academic institutes, several private and government townships.

2.3 Selection of Load Demand

The main type of load demand considered for this investigation are: residential sector, a grocery store, a non-residential school and an academic township. The main reason for this consideration is due to the diverse load profile and ease of availability of load data. The load profile for residential sector, non-residential school and a grocery store are likely to be vary due to different occupancy behaviour and time of use of appliances in these sectors and a small academic township is likely a representation of the cumulative load profiles of these different sectors together. The load demand used have been real data or synthetic data based on their availability on the specific site.

2.4 Selection of resources

The availability of various resources in the region have been identified in the form of solar radiation (kWh/m²/day), wind speed(m/s), average daily temperature (⁰C), biomass availability (tonnes/day) and hydrokinetic flow speed (m/s). Despite the state’s copious accessibility of various renewable energy sources (RESs) (21–24), the utilization of a specific resource for a particular type of load demand or site may be limited by challenges like localized unavailability and government regulations for biomass and hydropower (19,20), flat land unavailability and shading issues for ground mounted solar plants in congested urban locations (10,16,188), high costs and noise issues for wind (12) and odour issues for biogas (16). Hence specific resources have been considered for each case-study based on their suitability for the specific site and type of load demand.

2.5 System component design

The modelling of system components has been discussed in the following sub-sections:

2.5.1 Solar Panels

The solar panels absorb solar radiation and convert it to electrical energy. The PV power output is a function of incident global solar radiation, the temperature of the PV panel and the PV derating factor

(50,189). The PV derating factor is a scaling factor that considers the effects of various losses that would reduce the power output of the PV module than the expected ideal output (190). The power output of the PV array has been calculated by (50,189):

$$E_{PV} = E_{RPV} \times g_{PV} \times \left(\frac{\bar{I}_T}{I_{T,STC}} \right) \times [1 + \beta_P \times (T_c - T_{c,STC})] \quad (2.1)$$

where

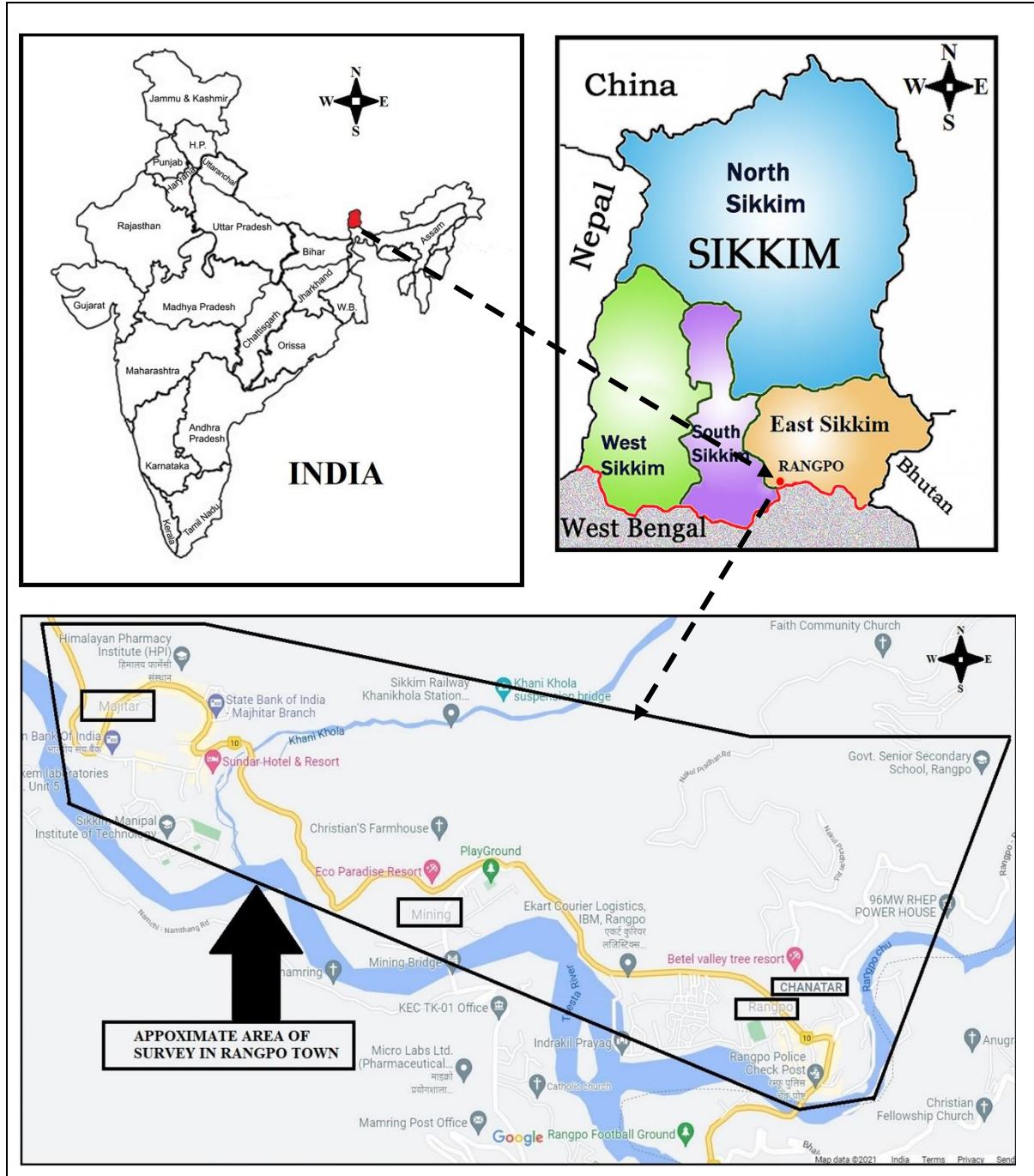


Figure 2.2 Location of area of the town [183-185]

$$T_c = \frac{T_a + \bar{I}_T \times \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{I_{T,NOCT}} \right) \times \left(1 - \frac{\eta_{mp}}{\alpha} \times \left(\frac{\eta_{mp,STC} \times (1 - \beta_P \times T_{c,STC})}{\tau \alpha} \right) \right)}{1 + (T_{c,NOCT} - T_{a,NOCT}) \times \left(\frac{\bar{I}_T}{I_{T,NOCT}} \right) \times \left(\frac{\beta_P \times \eta_{mp}}{\tau \alpha} \right)} \quad (2.2)$$

Where “ E_{RPV} is the rated capacity of the PV array (kW), g_{PV} is the PV derating factor (%), \bar{I}_T is the solar radiation incident on the PV array in the current time-step (kW/m^2), $\bar{I}_{T,STC}$ is the incident radiation at standard test conditions (kW/m^2), β_P is the temperature co-efficient of power ($\%/^{\circ}C$), T_c is the PV cell temperature in current time-step ($^{\circ}C$), $T_{c,STC}$ is the PV cell temperature under standard test conditions ($^{\circ}C$), T_a is the ambient temperature ($^{\circ}C$), η_{mp} is the electrical conversion efficiency of the PV array (%), $T_{c,NOCT}$ is the nominal cell operating temperature ($^{\circ}C$), $T_{a,NOCT}$ is the ambient cell temperature at which the nominal cell operating temperature is defined ($^{\circ}C$), $\bar{I}_{T,NOCT}$ is the solar radiation at which the nominal cell operating temperature is defined (kW/m^2), α is the solar absorptance of the PV array, τ is the solar transmittance of any cover over the PV array”.

2.5.2 Wind Turbine

A wind turbine transforms the kinetic energy of wind into electricity. The power produced by the wind turbine at a particular location depends on multiple factors such as density of air, altitude of the location, directions of wind, soil roughness factor, surrounding topography, temperature of the location etc (191). The modeling of the wind turbine has been done with the help of a particular kind of power curve which is a plot between power output and wind speeds at specific hub heights. The wind power output at standard temperature and pressure is given by (50,189):

$$P_{WTG,STP} = \frac{1}{2} \rho_0 A U_{hub}^3 \quad (2.3)$$

where

$$U_{hub} = U_{anem} \cdot \left(\frac{z_{hub}}{z_{anem}} \right)^{\alpha_p} \quad (2.4)$$

Where “ A is the cross-sectional area of the wind flowing across the turbine (m^2), U_{hub} is the wind speed at the hub height of the wind turbine (m/s), ρ_0 is the air density at standard temperature and pressure (1.225 kg/m^3), U_{anem} is the wind speed at anemometer height (m/s), z_{hub} is the hub height of the wind turbine (m), z_{anem} is the anemometer height (m), α_p is the power law exponent”.

The actual wind turbine performance is given by the following equation (50,189):

$$P_{WTG} = \frac{\rho}{\rho_0} \cdot P_{WTG,STP} \quad (2.5)$$

where, the density ratio is given by :

$$\frac{\rho}{\rho_0} = \left(1 - \frac{Bz}{T_0} \right)^{g/RB} \left(\frac{T_0}{T_0 - Bz} \right) \quad (2.6)$$

Where “ P_{WTG} is the wind turbine power output (kW), ρ is the actual air density (kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), B is the lapse rate (0.00650 K/m), z is the altitude (m), T_0 is the standard temperature (288.16 K), R is the gas constant (287 J/kgK)”.

2.5.3 Biomass Electrical Generation Unit

The electrical generation capacity of the biomass (biogas/syngas) electrical generation unit is given by the following relation (192):

$$P_E = \frac{E_B}{\eta_e T_c} \quad (2.7)$$

Where

$$E_B = \sum_{n=1}^i N_i m_i k_{DMi} k_{OMi} v_{Bi} e_{Bi} \quad (2.8)$$

Where “ m_i is the raw material available per person (kgs), N_i is the total number of persons in the campus, k_{DMi} is the dry matter content (total solids) in the raw material, k_{OMi} is the total organic matter content (volatile solids) in the dry matter, v_{Bi} is the specific biomass output from the organic matter (m^3/ton), e_{Bi} is the specific heat energy obtainable from raw material (kWh/m^3), E_B is the potential of the obtainable energy from raw material (kWh), η_e is the co-efficient of electrical efficiency

of the biomass electrical generation unit which is electrical efficiency of generator at the rated capacity (%), T_c is the total operation hours of the plant throughout the year”.

The electrical efficiency of the biomass generator has been defined by (50,193):

$$\eta_e = \frac{3.6P_E}{\rho_f(P_{gen}F_0 + P_E F_1)LHV_{fuel}} \quad (2.9)$$

Where “ η_e is the electrical efficiency of the biogas generator at rated capacity, P_E is the generator output power (kW), ρ_f is the density of the fuel (kg/m^3), P_{gen} is the rated generator power (kW), F_0 is the generator fuel curve intercept co-efficient ($m^3/h/rated kW$), F_1 is the fuel curve slope ($m^3/h/output kW$)”.

2.5.4 Hydro-kinetic turbines

Hydro-kinetic turbines operation and design principles are same as those of wind turbines except for the fact that they work with water whose density is much higher than air. Therefore, the available energy in a given flow stream for a hydrokinetic turbine is much larger than that for a wind turbine. Theoretically, hydrokinetic turbines can capture or extract only a portion of the kinetic energy of water that passes through its cross section. That maximum value of power extraction which is equal to 0.59 occurs when the exit velocity of flow from the turbine becomes one-third of the entry velocity (194). The hydrokinetic turbines are designed with an aim to reach this limit. The power output of a hydro kinetic turbine is given by the relation (194):

$$P_{HKT} = \frac{1}{2} C_P \rho_H A_H V^3 \quad (2.10)$$

where ρ_H is the water density ($1000 kg/m^3$), A_H is the turbine’s flow facing area (m^2), V is the instantaneous inflow velocity over the turbine’s flow facing area (m^2), “ C_P is the Betz limit for power extraction from the flowing water (0.59)”.

2.5.5 Battery

A battery is provided as a storage device in a DES in order to compensate for the unreliability of other renewable energy resources. Batteries capacities can range from a few watts to kilowatts. The maximum storage power is given by the following equation (50,189):

$$P_{batt,cmax} = \frac{MIN(P_{batt,cmax,kbm}, P_{batt,cmax,mcr}, P_{batt,cmax,ncc})}{\eta_{batt,c}} \quad (2.11)$$

Where

$$P_{batt,cmax,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-kt})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-kt})} \quad (2.12)$$

$$P_{batt,cmax,mcr} = \frac{(Q_{max} - Q)(1 - e^{-\alpha c t})}{\Delta t} \quad (2.13)$$

$$P_{batt,cmax,mcc} = \frac{N_{batt} I_{max} V_{nom}}{1000} \quad (2.14)$$

And the battery discharge power is given by:

$$P_{batt,dmax,kbm} = \frac{-kQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-kt})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-kt})} \quad (2.15)$$

And

$$\eta_{batt,d} = \eta_{batt,c} = \eta_{batt,rt} \quad (2.16)$$

Where “ $P_{batt,cmax,kbm}$ is the maximum power that can be stored by the two tank system (kW), $P_{batt,cmax,mcr}$ is the storage charge power corresponding to the maximum charge rate (kW), $P_{batt,cmax,mcc}$ is the storage charge power corresponding to the maximum charge current (kW), k is

the storage rate constant (h^{-1}), Δt is the length of the time step (h), c is the storage capacity ratio (unitless), Q_1 is the available energy in storage at the beginning of the time step (kWh), Q is the total amount of energy in the storage at the beginning of the time-step (kWh), α_c is the storage's maximum charge rate, Q_{max} is the total capacity of the storage tank (kWh), N_{batt} is the number of batteries in the storage bank, I_{max} is the storage's maximum charge current (A), V_{nom} is the storage's nominal voltage (V), $\eta_{batt,d}$ is the battery discharge efficiency, $\eta_{batt,c}$ is the battery charge efficiency (%) and $\eta_{batt,rt}$ is the battery round trip efficiency(%)”.

The battery throughput has been modelled according to the following equation (195):

$$E_{th} = E_n \times DOD \times C_f \quad (2.17)$$

Where “ E_n is the rated energy capacity of the battery (kWh), DOD is the depth of discharge, C_f is the number of charge-discharge cycles to failure”. The value of C_f at 80 % DOD is 1600 cycles (196,197).

2.5.6 Converter

A converter is needed for a DES to sustain and convert the flow of energy between A.C. and D.C systems. It consists of the inverter and the rectifier assembly. Their power output of a converter can be defined as follows for grid connected systems (50,189):

$$P_{inv,out} = \eta_{inv} P_{DC} \quad (2.18)$$

$$P_{rec,out} = \eta_{rec} P_{AC} \quad (2.19)$$

Where “ $P_{inv,out}$ is the power output of the inverter (kW), $P_{rec,out}$ is the power output of the rectifier (kW), η_{inv} is the inverter efficiency(%), η_{rec} is the rectifier efficiency, P_{AC} is the AC power input (kW), P_{DC} is the DC power input (kW)”.

The power converter modelling for standalone systems is given by (198):

$$C_{inv} \geq \left(\frac{\sigma_{sf}}{\eta_{inv}} \right) \times L_{max} \quad (2.20)$$

Where “ σ_{sf} is the factor of safety of the inverter (kW), η_{inv} is the inverter efficiency (%), L_{max} is the peak load (kW)”.

2.6 Modelling of Financial Parameters

The main cost output known as Levelized Cost of Energy (LCOE) is the average cost per kWh of useful electricity generated by the system and is calculated as (50):

$$LCOE = \frac{C_{ann,tot}}{E_{Served}} \quad (2.21)$$

where

$$C_{ann,tot} = CRF(i, R_{proj}) \cdot C_{NPC,tot} \quad (2.22)$$

where

$$i = \frac{i' - f}{1 + f} \quad (2.23)$$

and

$$CRF(i, R_{proj}) = \frac{i(1+i)^{R_{proj}}}{(1+i)^{R_{proj}} - 1} \quad (2.24)$$

Where “ $C_{ann,tot}$ is the annualized value of total net present cost ($\$/year$), E_{Served} is the total electrical load served (kWh/yr), $CRF(i, R_{proj})$ is the capital recovery factor, i is the real interest rate(%), i' is the nominal interest rate(%), f is the expected inflation rate, R_{proj} is the project lifetime (yrs), $C_{NPC,tot}$ is the total net present cost ($\$$)”.

Chapter 3 Case Study 1: Modeling of an autonomous hybrid Renewable Energy System for electrification of a township

3.1 Introduction

The potential of state's copious availability of various renewable energy sources (RESs) can be investigated in a location or site where there is abundant space for installation of a large DES and the DES is also located near a river or a running water source at a minimal distance and if the regulation aspects implemented by government on forest and river resources are ignored. Based on extensive literature reviews conducted in Chapter 1, it has been observed the potential of resources like biomass and hydrokinetic energy has not been investigated for any location in Sikkim apart from solar and wind. Based on these observations, the objectives of this cases-study were : i) to carry out a techno-economic feasibility study of an HRES meeting electrical energy demand for an academic township in the hilly terrain of north eastern Himalayan state of Sikkim, India, (ii) the other aspect of this work was to explore the potential of other renewable energy resources like biogas, syngas and hydrokinetic energy, in addition to mostly prevalent solar and wind energy in resource rich region. HRESs comprising of all the possible combinations of the above resources with batteries as back-up were analyzed for the least LCOE, minimum battery storage, minimum emissions, minimum area requirement and maximum employability potential as criteria. Various innovative constraints have been imposed in the analysis, (iii) to identify the best combination of the HRES on the basis of different criteria through Analytical Hierarchy process (AHP), a very prevalent multi-criteria decision-making (MCDM) technique, and lastly (iv) to carry out a sensitivity analysis for the best combination on the basis of different inflation rates, interest rates, hydrokinetic flow speeds, capital costs of hydrokinetic turbines, cost of syngas fuel and load demands to realize the behavior of the HRES on a broader perspective.

3.2 Methodology

A flowchart of the exact methodology used for this case study has been provided in **Figure 3.1**.

3.2.1 Site Description

The selected location was an academic township named Sikkim Manipal Institute of Technology in Majhitar, Sikkim, India located at 27° 10.6'N latitude, 88° 31.7'E longitude. The details of the location have been provided in **Figure 3.2**. The motivation for selection of this location was mainly due to ease of availability of real load data and other information needed for input into the HOMER software. Also, the campus is a mix of residential, official, commercial and mini-industrial buildings to give a rough perception of the load demand for any upcoming township or a small town within the region. The total area of the campus is 33 acres (133546.26 m²). The campus has two large academic buildings, five heavy machinery labs, four large hostels for students, four large residential buildings for faculties, a dispensary, a bank, a post office, a salon, four stationary shops, a sub-station for power and water supply. The total number of inhabitants inside the campus including students, teaching staff, non-teaching staff, labours and mess workers for 2018 was 2990. But the number dipped to about 1556 during the months of May, June, and December as most of the students and some of the faculties were on leave due to vacations during this period. The monthly average number of residents for the entire year has been estimated to be 2631.

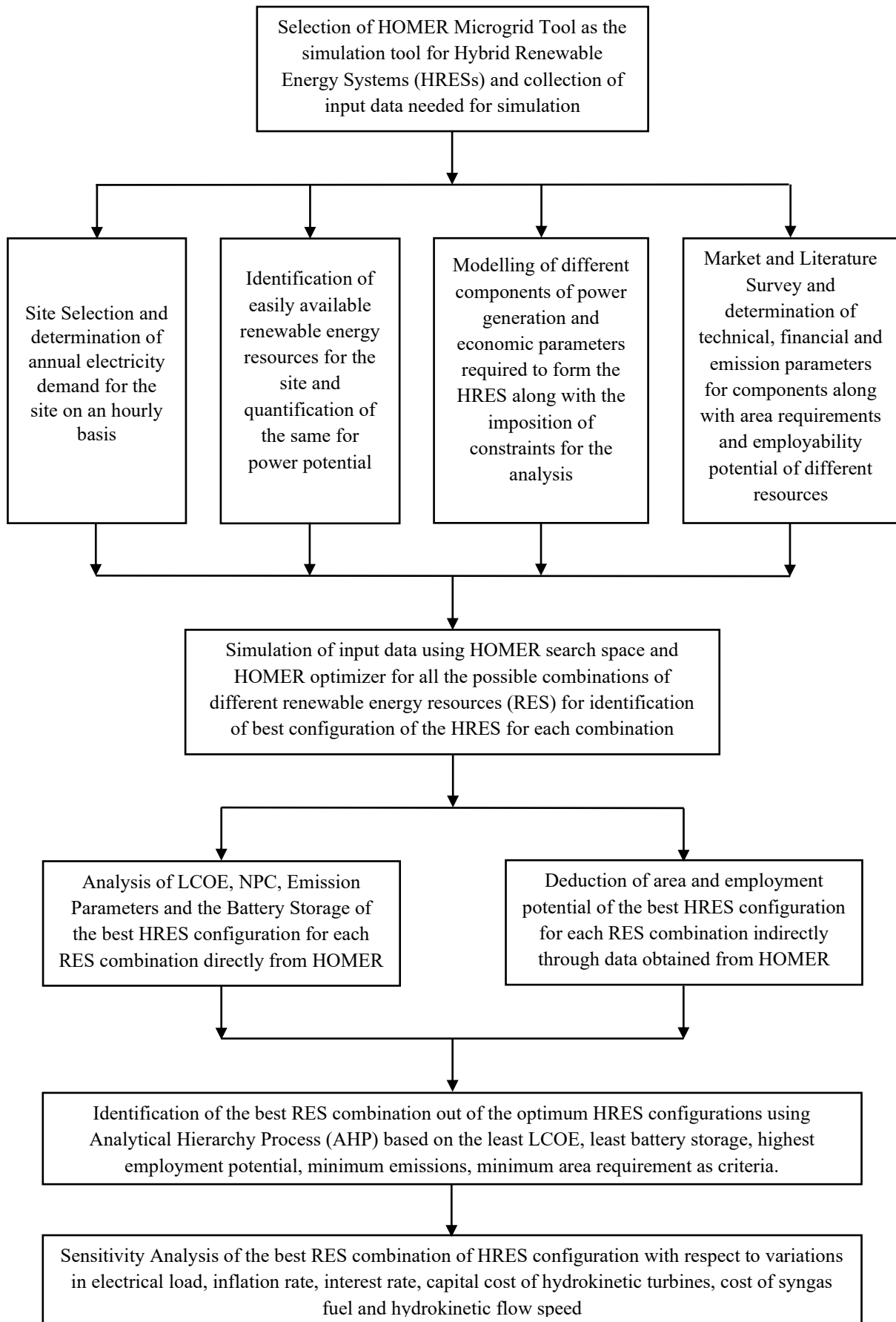


Figure 3.1 Methodology for the present analysis

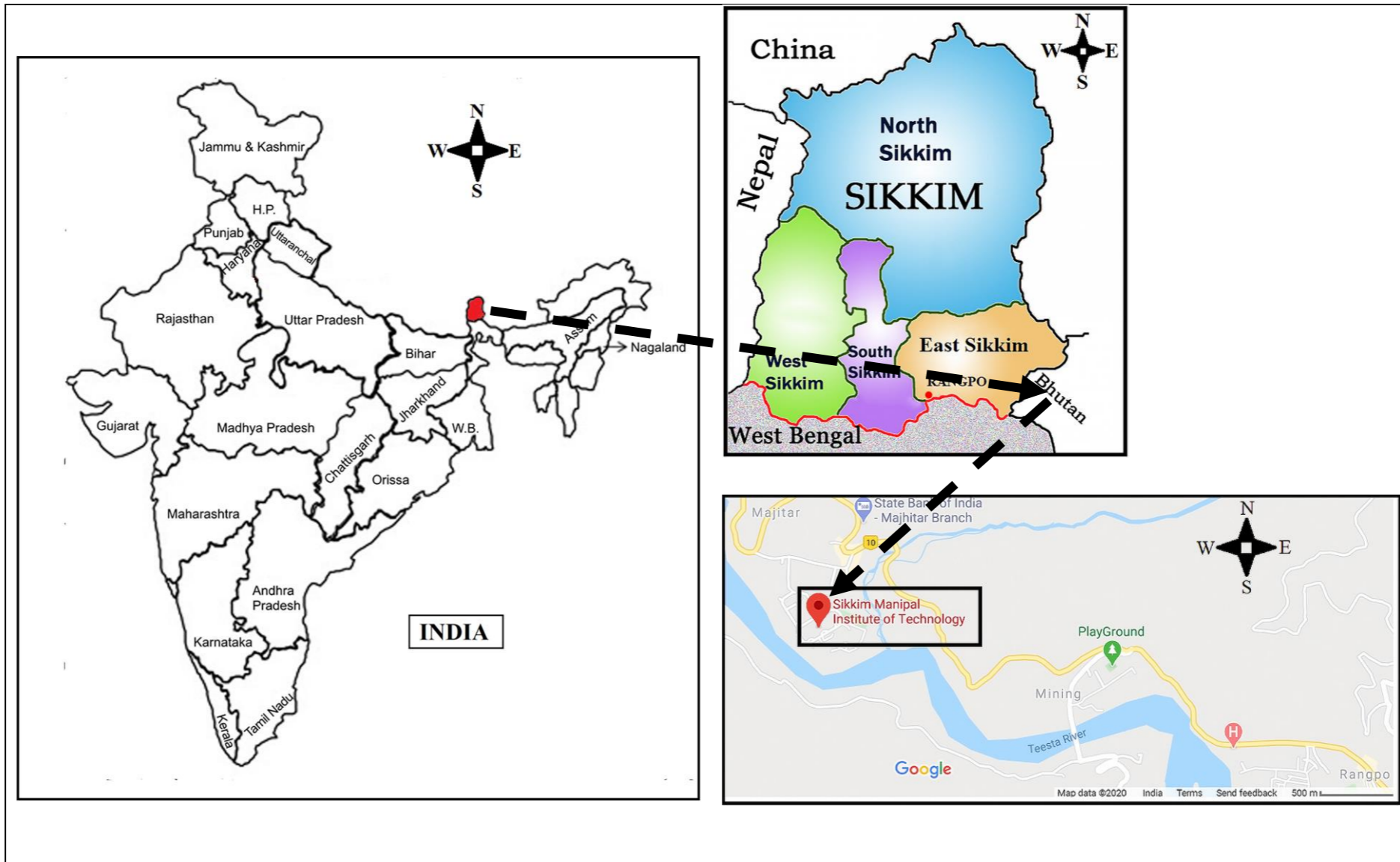


Figure 3.2 Location of the township area (199–201)

3.2.2 Load data

The township campus has a power sub-station which keeps record of the hourly electrical demand. Based on the information attained from the power sub-station, the township had an annual electrical requirement of 34,90,637 kWh/yr for the year 2018. The hourly peak load was 632 kW and the average hourly load was 389 kW. The load factor was 0.62. The hourly electrical load data has been presented in **Figure 3.3**.

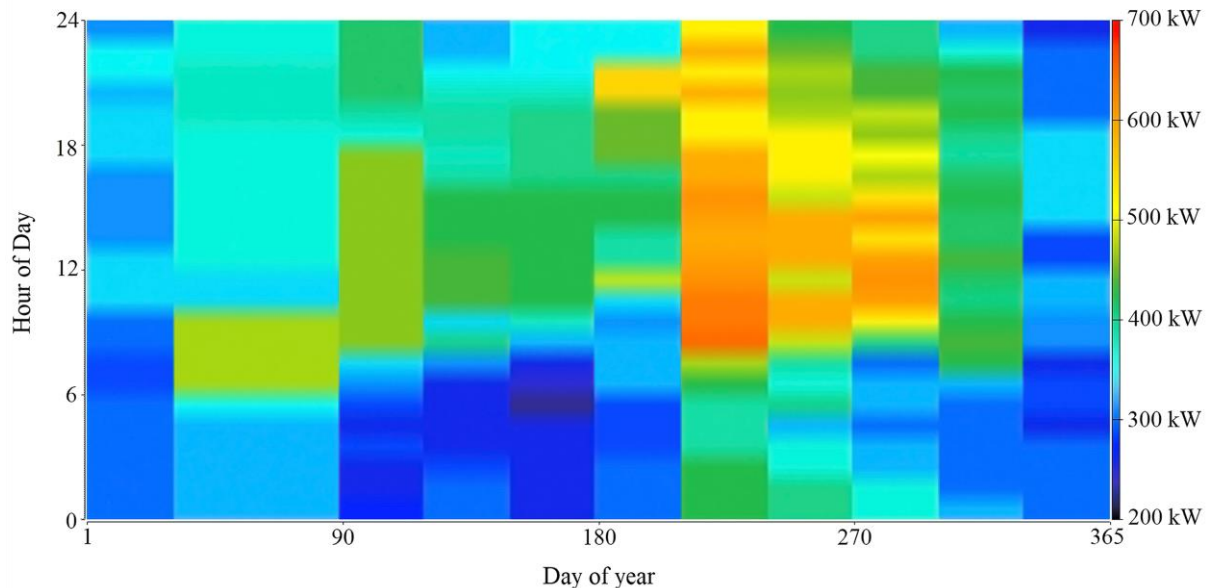


Figure 3.3 Hourly Electrical Demand for the selected township for the year 2018

3.2.3 Resource Availability Assessment

The selected location has a reasonably good availability of solar irradiation and wind speed (63). Hence these are attractive options for this site. The average monthly solar radiation data, the average monthly ambient temperature and the wind speed for this site were acquired from (199) and have been presented in **Figure 3.4**, **Figure 3.5** and **Figure 3.6** respectively. The average daily solar radiation and clearness index for the entire year is estimated to 4.79 kWh/m²/day and 0.546 respectively. The average daily temperature for the entire year was observed to be 8.94 °C. The selected region has a very salient wind speed profile experiencing average daily wind speeds of 5.71 m/s.

Biomass is also a promising source of energy in this region due to its richness in agricultural residues, forest wastes. The township produces considerable amounts of human wastes in the form of kitchen waste and sewage sludge. In the present analysis, biomass obtained from human excreta and food waste has been considered for biogas production and biomass obtained from forests wastes has been considered for syngas production due to their sufficient availability in the particular location. The average human excreta production day per capita is estimated to be .350 kgs (200) while the average food waste production per capita per day is estimated to be .300 kgs (201). Based on the average population estimate for the township, the average human excreta per day is 920.85 kgs and the average food wastage per day is 789.3 kgs respectively.

The township lies in East Sikkim District which had a surplus biomass of a 5.9 kilotonnes/year of agriculture residue and 52.3 kilotonnes/year of forest residue during a 2002-2004 survey (23). Assuming a 30% reduction in the biomass due to rapid industrialization and development of hydel power projects in the region (8,202) the present numbers have been estimated as 4 kilonnes/year of agriculture residue and 35 kilotonnes/ year of forest residue. Biomass potential for the township has been considered on a per capita basis from the surplus biomass available for the East Sikkim District. The estimated population of entire East Sikkim district is about 3,50,000 in 2019 (203). This gives an availability of 110 kgs/capita/year of surplus biomass. Therefore, the institute is entitled to get about 293 tonnes of biomass annually or 803.17 kgs/day on this basis. The biomass cost has been considered

after surveying the local market. The various other inputs for biogas production and syngas production have been provided in **Table 3.1**.

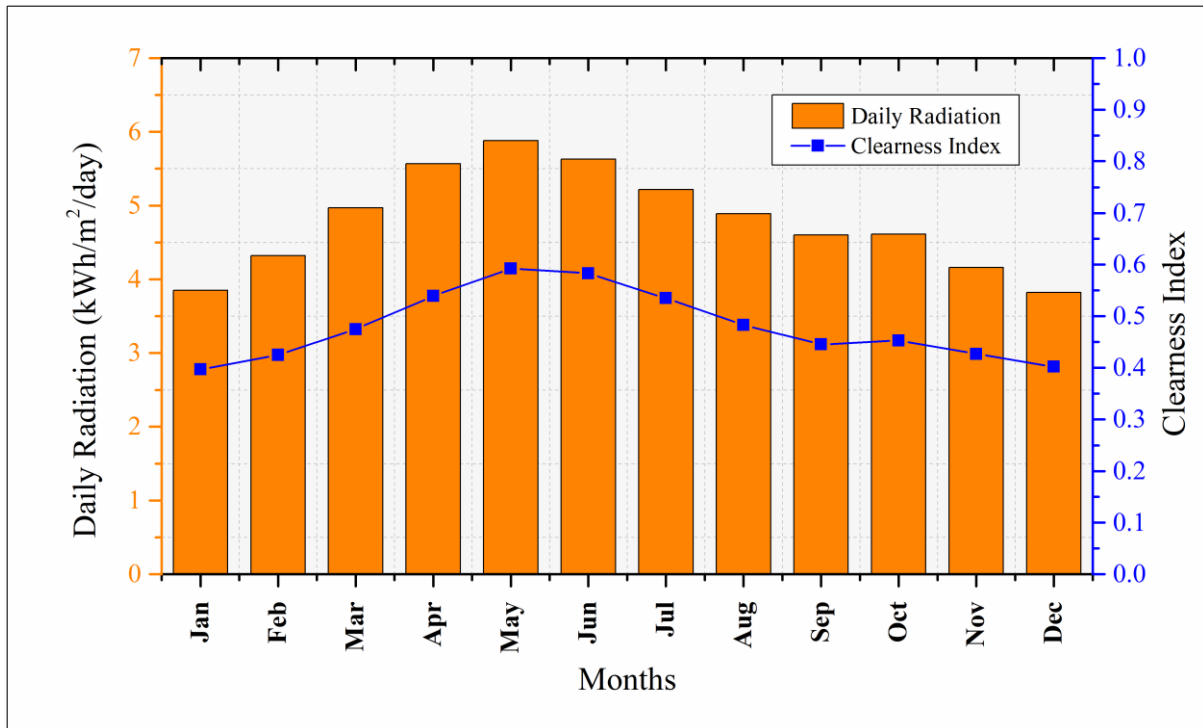


Figure 3.4 Monthly Average Solar Radiation

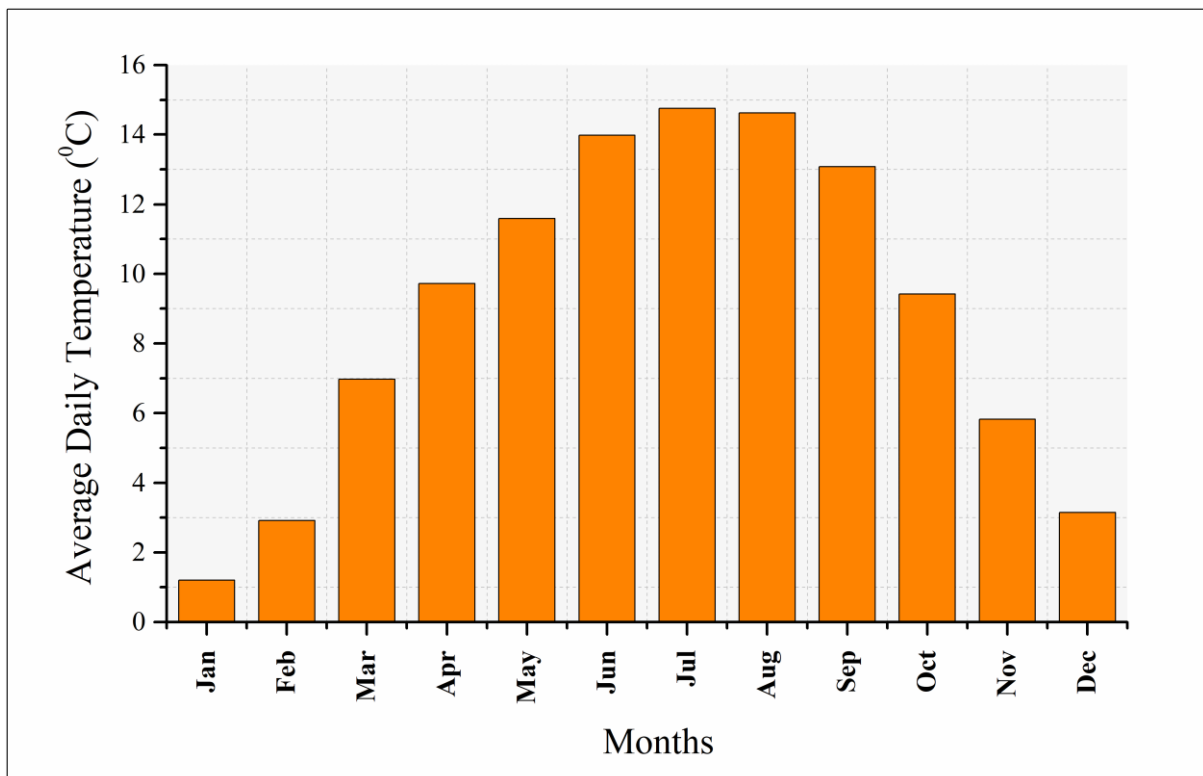


Figure 3.5 Monthly Average Temperature

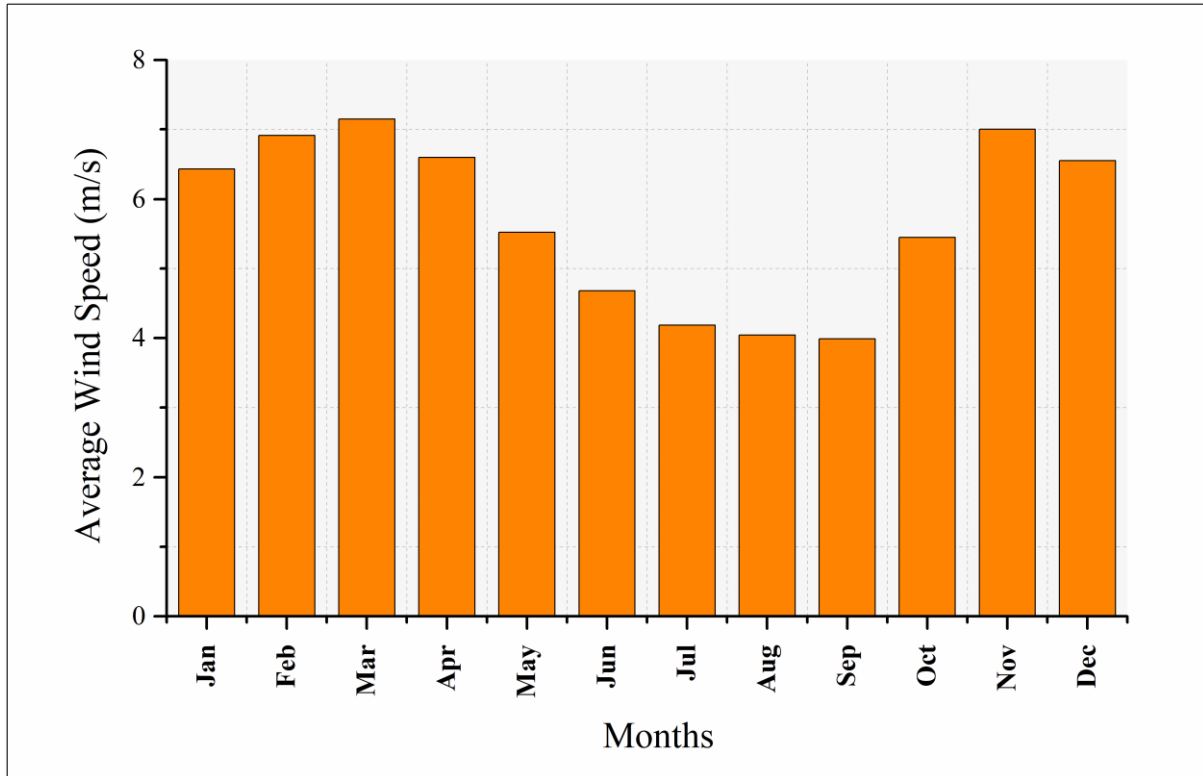


Figure 3.6 Monthly average wind speed

Table 3.1 Biomass Input Parameters for Biogas and Syngas

Fuel	Parameters	Value
Biogas (204)	Available Biomass (tonnes/day)	1.71
	Average Price (\$/tonne)	0
	Carbon Content (%)	55
	Density of Biogas (kg/m ³)	1.2
	LHV of biogas (MJ/kg)	18.58
Syngas (205–207)	Available Biomass (tonnes/day)	0.803
	Average Price (\$/tonne)	35.19
	Carbon Content (%)	45
	Density of Syngas (kg/m ³)	1.09
	LHV of syngas (MJ/kg)	4.65

The township is located very close to Teesta River in the lower foot hills of Sikkim where the speed of water fluctuates from about 2 m/s during winter to 4 m/s during rainy season (24). Since river Teesta’s span around the SMIT campus is about 1.5 kms, so the hydrokinetic potential of that distance has been taken into consideration in this study. The average water speed for the Teesta River has been presented in **Figure 3.7**. The river has a width of about 30 m and a depth of about 2 m in this span (24).

3.2.4 System component design and Financial Modelling

The modelling of system components was done with Equation 2.1 to Equation 2.20 (Chapter 2) while the financial modelling was done with Equation 2.21 to Equation 2.24.

The details of the power potential from biogas(200,201,208,209) and the syngas (205–207) have been deduced with the system component equations 2.7 and 2.8 based on the data provided in **Table 3.1** and **Table 3.3** and have been provided in **Table 3.3**

3.2.5 Technical and Financial Details of Various Equipment of the HRES

The prices and other technical parameters of different equipment were obtained from local Indians manufacturers and distributors. The rated capacities of different components were chosen based on availability within local markets. The fuel consumption-power plots and the efficiency-power curves

for the biogas generators and syngas generator have been presented in **Figure 3.8 (a)** to **Figure 3.8(f)** respectively. The efficiency curves were obtained once the values of F_0 and F_1 were deduced from the fuel consumption-power plot for the biogas and the syngas generators. A random reference capacity of 50 kW was chosen for both the biogas and syngas generators for which the fuel consumption to power details were available from manufacturer sheet (210). The details of the various deduced parameters for the generators have been provided in **Table 3.2**.

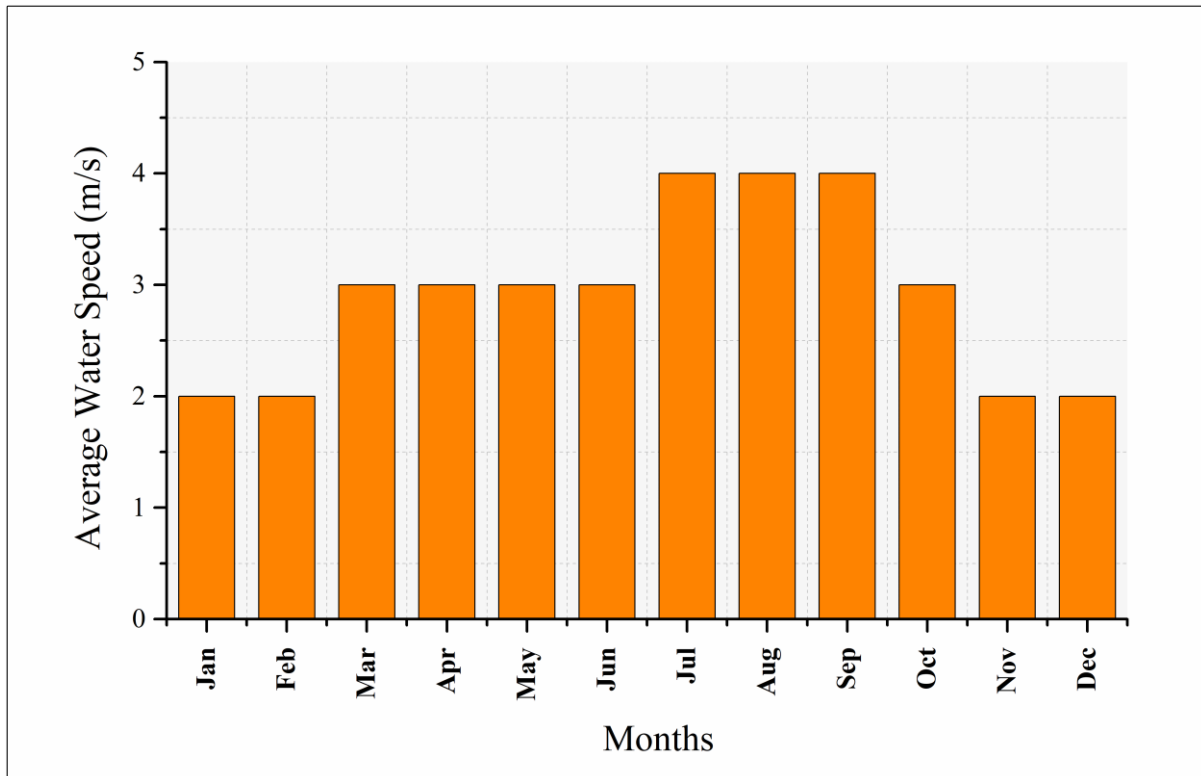


Figure 3.7 Monthly Average Speed of the Teesta River

The fuel cost is zero for biogas generator as the fuel comes from biogas produced from biomass. Since there is no place for specifying the capital costs of the biogas digester unit in HOMER tool, the capital costs along with the maintenance and operation costs of the biogas digester unit has been included in the costs of the biogas generator unit. The technical and financial details of the same have been provided in the **Figure 3.4** and **Table 3.5** respectively while, the area, emission and employment details have been provided in **Table 3.6**. Some of the remaining techno-economic data of different components have been provided in **Table 3.7**. The power curves considered for the wind turbine (191) and the hydrokinetic turbines considered in this study (211) have been presented in **Figure 3.9(a)** and **Figure 3.9(b)** respectively.

3.2.6 Constraints

Several limitations were imposed in this analysis. The maximum installation capacities of the PV panels, wind turbines, batteries and converters were considered on the basis that the area covered by them does not exceed 30 % of the area of the township campus. The maximum installation capacity of biogas generator was fixed on the basis of resource availability within the township and the maximum installation capacity of the syngas generators was limited by the resource availability on a per capita basis within the East Sikkim district area. The maximum number of hydrokinetic turbines was limited by the span of the Teesta River beside the institute available for installation. The minimum sizes or rated capacities of various components were considered on the basis of specifications locally available in the Indian market. The interest rates and inflation rates were assumed by considering the current interest rates and inflation rates prevailing in India.

The details of various constraints imposed in this analysis have been provided in **Figure 3.8**.

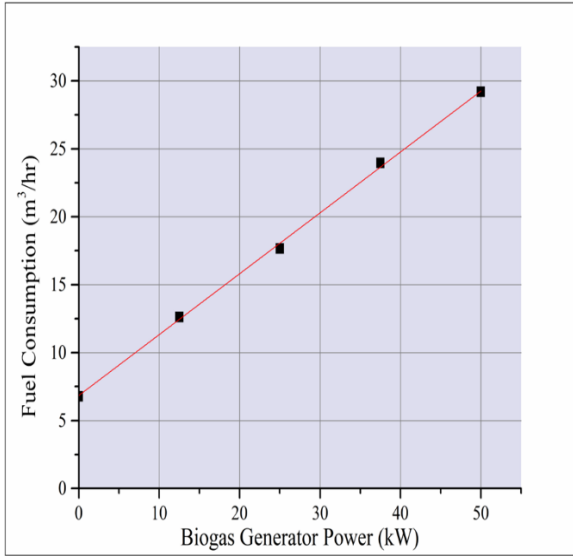


Fig. 3.8(a). Fuel -Power Plot for the Biogas Generator (50 kW)

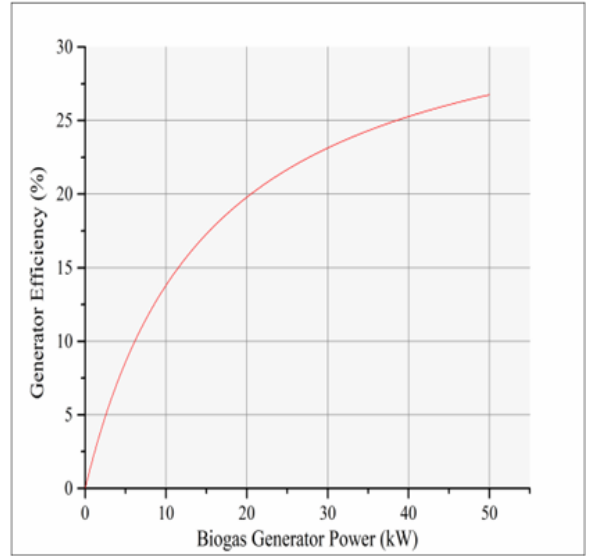


Fig. 3.8(b). Efficiency-Power Curve for the Biogas Generator (50 kW)

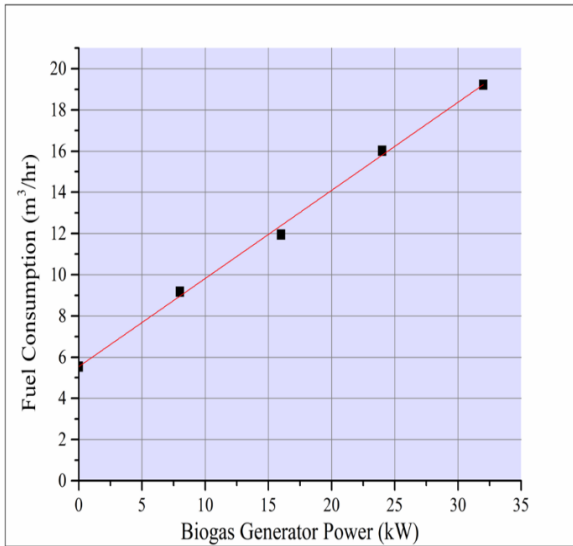


Fig.3.8(c) Fuel -Power Plot for the Biogas Generator (32 kW)

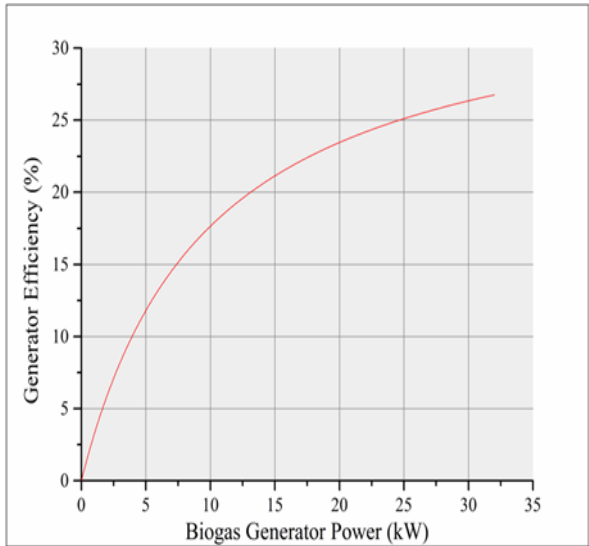


Fig. 3.8(d). Efficiency -Power Curve for the Biogas Generator (32 kW)

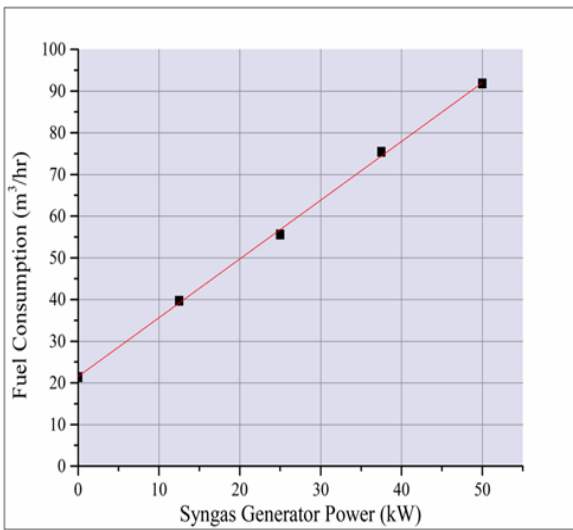


Fig. 3.8(e) Fuel -Power Plot for the Syngas Generator (50 kW)

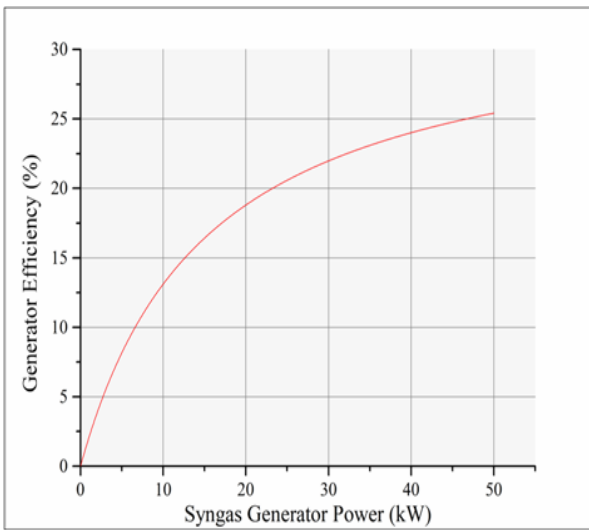


Fig. 3.8 (f). Efficiency-Power Curve for the Syngas Generator (50 kW)

Figure 3.8 Power Curves for Biogas Generators

Table 3.2 Deduced Generator parameters

Parameters	Biogas Generator	Biogas Generator	Syngas Generator
Reference Generator Capacity (kW)	50	32	50
Intercept Co-efficient (m ³ /h/kW rated) (F_0)	0.1372	0.1733	0.4321
Slope (m ³ /h/kW output) (F_1)	0.4481	0.4274	1.409
Efficiency at rated capacity (%) (η_e)	27	27	26

Table 3.3 Power Potential from Biomass for the township

Fuel	Type of raw material	Number of heads	Raw material available per head per year (tons/year)	Dry matter content	Organic Matter Content	Gas output (m ³ /ton)	Calorific Value of biogas (kWh/m ³)	Estimated power production (kW)
		N	m	k_{DM}	k_{OM}	v_B	e_B	P_E
Biogas	Human Excreta	2631	0.128	.20	.82	500	5.2	60.71
	Kitchen Waste	2631	0.109	.30	.95	400	5.2	71.87
Total estimated electricity production from biogas(kW/day)								132.58
Syngas	Agricultural Residue	2631	0.011	.90	.60	1600	1.38	14.68
	Forest Residue	2631	0.1	.90	.50	2000	1.38	143.47
Total estimated electricity production from syngas (kW/day)								158.15

Table 3.4 Technical Details of Various Components

Component	Parameter	Value
PV System (50,190,212)	Rated Capacity of each PV module(E_{RPV})	330 W
	Derating Factor(g_{PV})	88 %
	Nominal Operating Cell Temperature($T_{c,NOCT}$)	44°C
	Temperature Co-efficient(β_p)	-0.41 %/°C
	Efficiency at Standard Conditions(η_c)	17.01 %
Wind System (50,191)	Rated Power	5 kW
	Rotor Diameter	4.88 m
	Hub Height	10 m
Biogas System (213)	Rated Capacity of Biogas Generator (Quantity)	50 kW (2) & 32 kW (1)
Syngas System (213)	Rated Capacity of Syngas Generator (Quantity)	50 kW (3)
Hydrokinetic System (211)	Rated Capacity of the Generator	5 kW
	Optimum river flow velocity for maximum power output of 5 kW	2.8 m/s
	Maximum distance of Injection point from the turbine	500 m
	Lowest river velocity	1.5 m/s
	Highest river velocity	3.5 m/s
Lowest river depth	2 m	
Battery (212,213)	Rated Capacity	2.4 kWh
	Round Trip Efficiency	85 %
	Least State of Charge	20%
	Rectifier Efficiency	98.7 %
Converter (212,213)	Rated Capacity	50 kW
	Inverter Efficiency	98.3%
	Rectifier Efficiency	98.7 %

Table 3.5 Financial Details of Various Components

Component Details	Capital Costs (USD)	Replacement Costs (USD)	Fuel Costs (USD)/kWh	Operation & Maintenance Costs (USD)	Component Life
PV System (212,214)	469.03/kW	469.03/kW	-	150/year	25 yrs
Wind System (191)	997 /kW	997 /kW	-	150/year	20 yrs
Biogas System (213)	453 /kW	453 /kW	0	0.5 /hour	45000 hs
Syngas System (213)	719.29 /kW	719.29 /kW	0.014	0.5 /hour	45000 hs
Hydrokinetic System (211)	3174/kW	3174/kW	-	200/year	10 yrs

Battery (212,213)	\$216.78/battery	160.47/battery	-	5/year	5 yrs
Converter (212,213)	65/kW	65/kW	-	10/year	15 yrs

Table 3.6 Area, Emission and Employment Details of Various Components

Component Details	Area Required	NO _x Emission	CO Emission	Employment Potential (10 ⁻⁷ /kWh/yr)
PV System (2,212)	1.94 m ² / module	-	-	0.27549
Wind System (2,191)	.92 m ² /turbine	-	-	0.27549
Biogas System (2,213,215)	13.44 m ² /kW	3.4 g/m ³	5.38 g/m ³	0.27549
Syngas System (2,213,215)	2.93 m ² /kW	1.57 g/m ³	3.56 g/m ³	8.33
Hydrokinetic System (2,211)	5 m ² / turbine	-	-	0.87095
Battery (213)	0.095 m ² /battery	-	-	-
Converter (213)	464 m ² / converter	-	-	-

Table 3.7 Techno-Economic Details of Various Components

Component	Parameter	Value
PV System (50,190,212,214)	The cell temperature under standard test conditions ($T_{c,STC}$)	25°C
	The incident radiation at standard test conditions ($\bar{I}_{T,STC}$)	1 kW/m ²
	Ambient Cell Temperature ($T_{a,NOCT}$)	20 °C
	Solar radiation at which the nominal cell operating temperature is defined ($\bar{I}_{T,NOCT}$)	0.8 kW/m ²
	Weight	20.7 kgs
	Tracking System	Maximum power point
	Capital Cost of PV panel	\$316.25/kW
	Replacement Cost of Panel	\$316.25/kW
	Solar Mounting Structure Price (Ground/Rooftop)	\$ 48.61/kW
	Solar Distribution Box prices	\$ 4.17/kW
	Miscellaneous Costs (Wiring, Transportation, Taxes)	\$ 100/kW
Wind System (50,191)	Number of Rotor Blades	3
	Axis	Horizontal
	Cut-in Wind Speed	3 m/s
	Survival Wind Speed	60 m/s
	Startup Wind Speed	2 m/s
	Capital Costs of the Wind Turbine	3850\$
	Replacement Cost	3850\$
	Capital Costs of the Wind Turbine Pole	633.80 \$
	Miscellaneous Expenses (Wiring, Transportation, Taxes)	500 \$
Biogas (213)	Total Installation Area of the Biogas Digester	38.47 m ²
	Total Installation Area for a 50 kW Generator Room	15.36m ²
	Slurry Storage Tank Area	5 m ²
	Pre-Treatment Chamber Area	5 m ²
	Area of the Gas Holder Room	17.64 m ²
	Storage for Miscellaneous Items	5 m ²
Syngas (213)	Area for storing Biomass waste	100 m ²
	Area required for the producer gas generator	46.45 m ²
	Area for storing Biomass waste	100 m ²
Hydrokinetic (211)	Power output range of the generator	0.250 kW -5kW
	Rotational Speed	900-2300 rpm
	Highest river width	2 m
	Highest installation depth of generator	10 m
Battery (212,213)	Battery Type	Lead Acid
	Minimal Voltage	12 V
	Minimal Capacity	200 Ah

Table 3.8 Details of constraints imposed in this study

Parameters	Value
Interest Rate	8%
Inflation Rate	3.5%
Annual Capacity Shortage	0%
Project lifetime	25 years
Maximum number of PV panels	17389 (330 W each)

Maximum Number of Wind Turbines	36290 (5 kW each)
Maximum number of Batteries	351436 (2.4 kWh each)
Maximum Number of Converters	72 (50 kW each)
Maximum Number of Hydrokinetic Turbines	60 (5 kW each)
Maximum Number of Biogas Generators	2 (50 kW each), 1 (32 kW)
Maximum Number of Syngas Generators	3 (50 kW each)

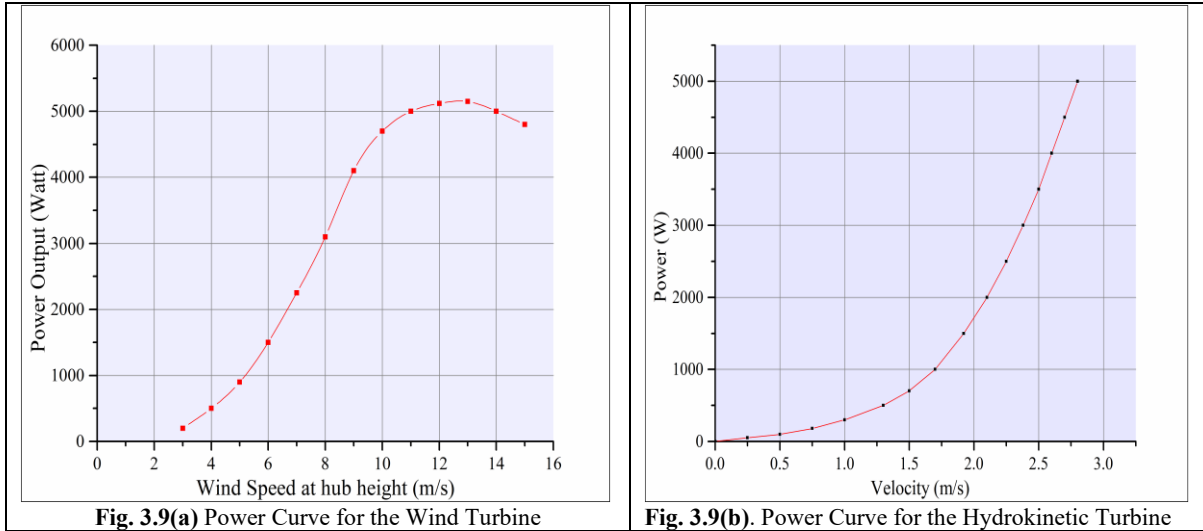


Fig. 3.9(a) Power Curve for the Wind Turbine

Fig. 3.9(b). Power Curve for the Hydrokinetic Turbine

Figure 3.9 Power Curve for Wind and Hydrokinetic Turbines

3.2.7 Limitations of Methodology

In the present methodology, the variations of load demand within an hour were not considered as the power sub-station department only recorded the load demand on an hourly basis. In addition to that, HOMER Pro does not consider the variations in voltage and current fluctuations from the supply side and only considers them in the form of power output as a whole. Other contingencies like loss of power generation, transmission losses, failure of devices were neglected. Due to exclusion of these aspects, the analysis provided an approximate result rather than an exact one. However, inclusion of those aspects while computing for multiple resources will complicate and elongate the already lengthy simulations of a software like HOMER and will require very high performance and expensive computing facilities than the one currently used for this analysis. Despite the limitations, HOMER still manages to provide several detailed theoretical results in proximity of actual results (50) and is a widely used tool worldwide for this type of analysis (50,183–185) and hence has been used in this study.

3.3 Results

The proposed configurations of the HRES were simulated in HOMER Pro Microgrid Tool using the available financial and technical database. All the 31 combinations of renewable energy were considered and simulated on an hourly basis. The configuration of one of the combinations has been presented in **Figure 3.10**. The results of optimal configurations of different combinations have been provided in **Table 3.10** and are discussed in the following sub-sections.

3.3.1.1 Combination 1: PV-Battery System

The best system configuration for this combination consisted of 12200 PV modules of 330 W each, 16667 batteries of 2.4 kWh each and 15 converters of 50 kW each. The Net Present Cost (NPC) of the system was 18.8 million US \$ with the Levelized Cost of Energy (LCOE) as 0.357 \$/kWh. There were no GHG emissions from the system. The minimum area needed for the system is 32212 m². The system had an employment potential of 0.18 persons/year.

3.3.1.2 Combination 2: Wind-Battery System

The best configuration consisted of 1813 wind turbines of 5 kW each, 40625 batteries and 44 converters. The NPC was 32.3 million US \$ with the LCOE as 0.615 \$/kWh. There were no emissions. The

minimum area requirement and the employment potential were 25944 m² and 0.44 persons/year respectively.

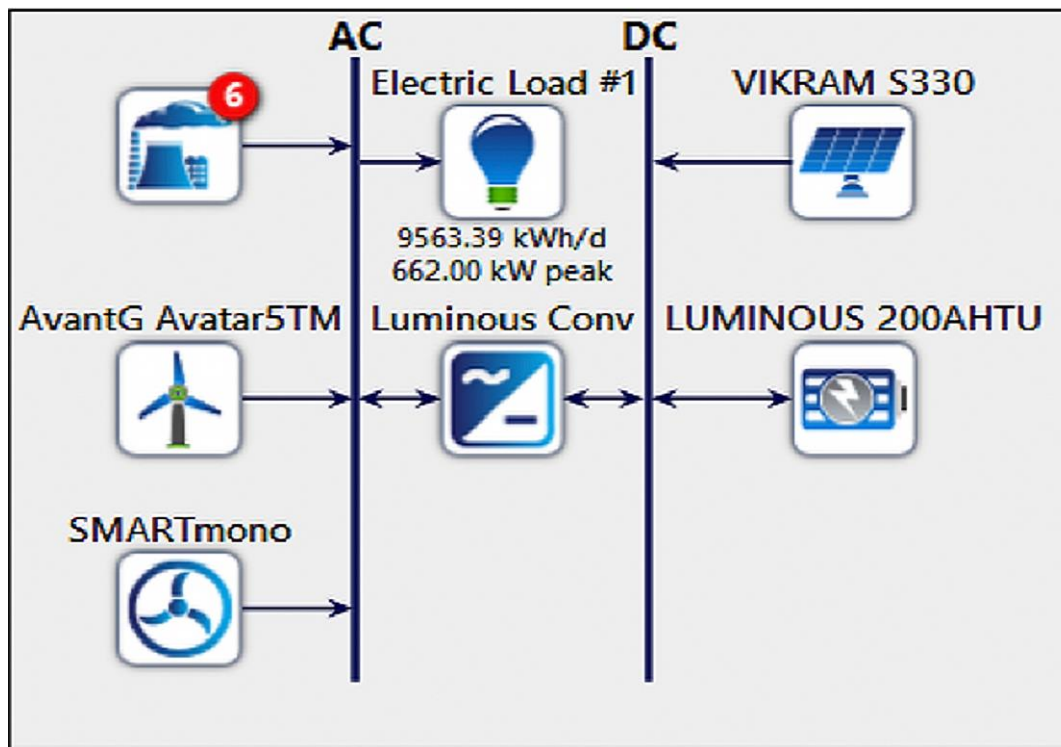


Figure 3.10 Schematic Diagram of an HRES generated by HOMER Pro (Combination 31)

3.3.1.3 Combination 6: PV-Wind-Battery System

The best configuration consisted of 13000 panels, 291 wind turbines, 13290 batteries and 15 converters. The NPC was 16.2 million US \$ with the LCOE as 0.308 \$/kWh. There were no GHG emissions. The minimum area requirement and the employment potential were 28237 m² and 0.24 persons/year respectively.

3.3.1.4 Combination 7: PV-Biogas-Battery System

The best configuration consisted of 10000 solar panels, 2 biogas generators of 50 kW each, 1 biogas generator of 32 kW, 12240 batteries and 14 converters. The NPC was 14.8 million US \$ with the LCOE as 0.281 \$/kWh. The annual GHG emissions included 977788 kgs of CO₂, 7679 kgs of CO and 4852 kgs of NO_x. The minimum area requirement and the employment potential were 28833 m² and 0.17 persons/year respectively.

3.3.1.5 Combination 8: PV-Syngas-Battery System

The best configuration consisted of 9800 solar panels, 3 syngas generators of 50 kW each, 11458 batteries and 14 converters. The NPC was 14.50 million US \$ with the LCOE as 0.275 \$/kWh. The annual GHG emissions included 1136517 kgs of CO₂, 7932 kgs of CO and 3491 kgs of NO_x. The minimum area requirement and the employment potential were 27036 m² and 0.80 persons/year respectively.

3.3.1.6 Combination 9: PV-Hydrokinetic-Battery System

The best configuration consisted of 6000 solar panels, 60 hydrokinetic turbines of 5 kW each, 6510 batteries and 9 converters. The total NPC was 9.58 million US \$ with the LCOE as 0.182 \$/kWh. There were no GHG emissions. The minimum area requirement and the employment potential were 16735 m² and 0.27 persons/year respectively.

3.3.1.7 Combination 10: Wind-Biogas-Battery System

The best configuration consisted of 1875 wind turbines, all the 3 biogas generators, 29167 batteries and 26 converters. The total NPC was 38.40 million US \$ with the LCOE as 0.731 \$/kWh. The annual GHG emissions included 523089 kgs of CO₂, 1158 kgs of CO and 732 kgs of NO_x. The minimum area requirement and employment potential were 15445 m² and 0.39 persons/year respectively.

3.3.1.8 Combination 11: Wind-Syngas-Battery System

The best configuration consisted of 1860 wind turbines, all the 3 syngas generators, 27604 batteries and 23 converters. The NPC was 37.4 million US \$ with the LCOE as 0.712 \$/kWh. The annual GHG emissions included 603781 kgs of CO₂, 4213 kgs of CO and 1854 kgs of NO_x. The minimum area requirement and the employment potential were 9122 m² and 0.72 persons/year respectively.

3.3.1.9 Combination 12: Wind-Hydrokinetic-Battery System

The best configuration consisted of 1101 wind turbines, all the 60 hydrokinetic turbines, 15400 batteries and 13 converters. The NPC was 22.7 million US \$ with the LCOE as 0.432 \$/kWh. There were no GHG emissions. The minimum area requirement and the employment potential were 8808 m² and 0.40 persons/year respectively.

3.3.1.10 Combination 15: Syngas-Hydrokinetic-Battery System

The best configuration consisted of all the 3 syngas generators, all the 60 hydrokinetic turbines, 300000 batteries and 6 converters. The NPC was 232 million US \$ with the LCOE as 4.40 \$/kWh. The annual GHG emissions included 1428762 kgs of CO₂, 9879 kgs of CO and 4353 kgs of NO_x. The minimum area requirement and the employment potential were 32024 m² and 0.99 persons/year respectively.

3.3.1.11 Combination 16: PV-Wind-Biogas Battery

The best configuration consisted of 14900 solar panels, 339 wind turbines, all the 3 biogas generators, 6667 batteries and 12 converters. The total NPC was 13.3 million US \$ with the LCOE as 0.253 \$/kWh. The annual GHG emissions included 665344 kgs of CO₂, 1473 kgs of CO and 930 kgs of NO_x. The minimum area requirement and the employment potential were 37194 m² and 0.31 persons/year respectively.

3.3.1.12 Combination 17: PV-Wind-Syngas Battery

The best configuration consisted of 4323 solar panels, 71 wind turbines, all the 3 syngas generators, 9036 batteries and 14 converters. The NPC was 13.7 million US \$ with the LCOE as 0.261 \$/kWh. The annual GHG emissions included 1057975 kgs of CO₂, 7384 kgs of CO and 4347 kgs of NO_x. The minimum area requirement and the employment potential were 33274 m² and 0.82 persons/year respectively.

3.3.1.13 Combination 18: PV-Wind-Hydrokinetic Battery

The best configuration consisted of 7500 solar panels, 142 wind turbines, all the 60 hydrokinetic turbines, 3602 batteries and 12 converters. The total NPC was 8.34 million US \$ with the LCOE as 0.159 \$/kWh. There were no GHG emissions. The minimum area requirement and the employment potential were 20591 m² and 0.33 persons per year respectively.

3.3.1.14 Combination 19: PV-Biogas-Syngas Battery

The best configuration consisted of 8200 solar panels, all the 3 biogas generators, all the 3 syngas generators, 5938 batteries and 14 converters. The NPC was 10.50 million US \$ with the LCOE as 0.199 \$/kWh. The annual GHG emissions included 2087205 kgs of CO₂, 9809 kgs of CO and 4746 kgs of NO_x. The minimum area requirement and the employment potential were 25182 m² and 0.77 persons/year respectively.

3.3.1.15 Combination 20: PV-Biogas-Hydrokinetic Battery

The best configuration consisted of 4300 solar panels, all the 3 biogas generators, all the 60 hydrokinetic turbines, 2708 batteries and 8 converters. The NPC was 6.64 million US \$ with the LCOE as 0.126 \$/kWh. The annual GHG emissions included 689736 kgs of CO₂, 1527 kgs of CO and 964 kgs of NO_x. The minimum area requirement and the employment potential were 14386 m² and 0.26 persons/year respectively.

3.3.1.16 Combination 21: PV-Syngas-Hydrokinetic Battery

The best configuration consisted of 1353 solar panels, 51 wind turbines, all the 3 syngas generators, all the 60 hydrokinetic turbines, 2292 batteries and 9 converters. The NPC was 6.64 million US \$ with the LCOE as 0.126 \$/kWh. The annual GHG emissions included 769670 kgs of CO₂, 5372 kgs of CO and 2367 kgs of NO_x. The minimum area requirement and the employment potential were 13088 m² and 0.68 persons/year respectively.

3.3.1.17 Combination 22: Wind-Biogas-Syngas Battery

The best configuration consisted of 1228 wind turbines, all the 3 biogas generators, all the 3 syngas generators, 21021 batteries and 25 converters. The NPC was 20.2 million US \$ with the LCOE as 0.384 \$/kWh. The annual GHG emissions included 1242914 kgs of CO₂, 5656 kgs of CO and 2737 kgs of NO_x. The minimum area requirement and the employment potential are 16941 m² and 0.61 persons/year respectively.

3.3.1.18 Combination 23: Wind-Biogas-Hydrokinetic Battery

The best configuration consisted of 638 wind turbines, all the 3 biogas generators, all the 60 hydrokinetic turbines, 7558 batteries and 11 converters. The NPC was 13.7 million US \$ with the LCOE as 0.261 \$/kWh. The annual GHG emissions included 409656 kgs of CO₂, 907 kgs of CO and 573 kgs of NO_x. The minimum area requirement and the employment potential were 8483 m² and 0.32 persons/year respectively.

3.3.1.19 Combination 24: Wind-Syngas-Hydrokinetic Battery

The best configuration consisted of 563 wind turbines, all the 3 syngas generators, all the 60 hydrokinetic turbines, 6882 batteries and 11 converters. The NPC was 12.9 million US \$ with the LCOE as 0.245 \$/kWh. The annual GHG emissions included 473785 kgs of CO₂, 3307 kgs of CO and 1457 kgs of NO_x. The minimum area requirement and the employment potential were 7015 m² and 0.56 persons/year respectively.

3.3.1.20 Combination 25: Biogas-Syngas-Hydrokinetic Battery

The best configuration consisted of the all the 3 biogas generators, all the 3 syngas generators, all the 60 hydrokinetic turbines, 32552 batteries and 3 converters. The NPC was 30.3 million US \$ with the LCOE as 0.577 \$/kWh. The annual GHG emissions included 2017757 kgs of CO₂, 8325 kgs of CO and 1457 kgs of NO_x. The minimum area requirement and the employment potential were 6998 m² and 0.66 persons/year respectively.

3.3.1.21 Combination 26: PV-Wind-Biogas-Syngas Battery

The best configuration consisted of 7400 solar panels, 220 wind turbines, all the 3 biogas generators, all the 3 syngas generators, 4531 batteries and 13 converters. The NPC was 10 million US \$ with the LCOE as 0.191 \$/kWh. The annual GHG emissions included 1599654 kgs of CO₂, 8390 kgs of CO and 4060 kgs of NO_x. The minimum area requirement and the employment potential were 23235 m² and 0.60 persons/year.

3.3.1.22 Combination 27: PV-Wind-Biogas-Hydrokinetic Battery

The best configuration consisted of 1188 solar panels, 71 wind turbines, all the 3 biogas generators, all the 60 hydrokinetic turbines, 1667 batteries and 8 converters. The NPC was 5.92 million US \$ with the LCOE as 0.113 \$/kWh. The annual GHG emissions included 558691 kgs of CO₂, 1237 kgs of CO and 781.67 kgs of NO_x. The minimum area requirement and the employment potential were 12994 m² and 0.26 persons/year respectively.

3.3.1.23 Combination 28: PV-Wind-Syngas-Hydrokinetic Battery

The best configuration consisted of 3200 solar panels, 85 wind turbines, all the 3 syngas generators, all the 60 hydrokinetic turbines, 1354 batteries and 8 converters. The total NPC was 5.94 million US \$ with the LCOE as 0.113 \$/kWh. The annual GHG emissions included 589879 kgs of CO₂, 4116 kgs of CO and 1813 kgs of NO_x. The minimum area requirement and the employment potential were 10867 m² and 0.58 persons/year respectively.

3.3.1.24 Combination 29 PV-Biogas-Syngas-Hydrokinetic Battery

The best configuration consisted of 2700 solar panels, the 3 biogas generators, all the 3 syngas generators, all the 60 hydrokinetic turbines, 250 batteries and 9 converters. The NPC was 5.19 million US \$ with the LCOE as 0.099 \$/kWh. The annual GHG emissions included 1110413 kgs of CO₂, 4342 kgs of CO and 2101 kgs of NO_x. The minimum area requirement and the employment potential were 11952 m² and 0.47 persons/year respectively.

3.3.1.25 Combination 30: Wind-Biogas-Syngas-Hydrokinetic Battery

The best configuration consisted of 268 wind turbines, all the 3 biogas generators, all the 3 syngas generators, all the 60 hydrokinetic turbines, 833 batteries and 3 converters. The NPC was 6.53 million US \$ with the LCOE as 1.24 \$/kWh. The annual GHG emissions included 898571 kgs of CO₂, 3422 kgs of CO and 1656 kgs of NO_x. The minimum area requirement and the employment potential were 4231 m² and 0.41 persons/year respectively.

3.3.1.26 Combination 31: PV-Wind-Biogas-Syngas-Hydrokinetic Battery

The best configuration consisted of 1700 solar panels, 51 wind turbines, all the 3 biogas generators, all the 3 syngas generators, all the 60 hydrokinetic turbines, 156 batteries and 7 converters. The NPC was 5 million US \$ with the LCOE as 0.095 \$/kWh. The annual GHG emissions included 990301 kgs of CO₂, 3644 kgs of CO and 1764 kgs of NO_x. The minimum area requirement and the employment potential were 9122 m² and 0.40 persons/year respectively.

3.3.1.27 Infeasible solutions at 0% capacity shortage

A total of 5 combinations failed to produce feasible solutions at 0% capacity shortage. This were Combination 3 (Biogas-Battery), Combination 4 (Syngas-Battery), Combination 5 (Hydrokinetic-Battery), Combination 13 (Biogas-Syngas-Battery) and Combination 14 (Biogas-Hydrokinetic Battery). The power generated by these combinations was not able to supply the entire load without any unmet load.

3.3.2 Comparison of Results for different criteria

Combination 31 provides the lowest NPC and LCOE and needs the lowest battery bank storage among all the combinations. Combination 15 generates the highest number of jobs among all the combinations. Combination 30 requires the least area for installation among all the combinations. Combinations 1, 2, 6, 9, 12 and 18 produce the least GHG emissions among all the combinations. It was also observed that the HRESs employing multiple energy resources were generally cheaper than the HRESs employing single energy resources.

3.3.3 Identification of the best combination based on different criteria

It has been observed from the results that no single combination was a clear winner in all the criteria. Therefore, Analytical Hierarchy Process (AHP) was utilized to identify the best combination. The Analytical Hierarchy Process (AHP) is a general theory of measurement widely applicable in multicriteria decision making problems. It considers several criteria simultaneously, then analyses the dependence of the criteria on each other and considers the importance of each criterion over the other and finally makes numerical tradeoffs to arrive at a conclusion or decision (216). The details of the fundamental scale for comparison of different criteria have been provided in **Table 3.9** (216).

Table 3.9 Fundamental Scale for Comparison of Different Ideas in AHP

“Intensity of Importance of criteria on an absolute scale”	“Definition”	“Explanation”
1	“Equal Importance”	“Two criteria contribute equally to the objective”
3	“Moderate Importance of one over another”	“Experience and judgement strongly favor one criterion over another”
5	“Essential or strong importance”	“Experience and judgement strongly favor one criterion over another”
7	“Very strong importance”	“A criterion is strongly favored and its dominance is demonstrated in practice”
9	“Extreme Importance”	“The evidence favoring one criterion over another is of the highest possible order of affirmation”
“2, 4, 6, 8”	“Intermediate values between the two adjacent judgements”	“When compromise is needed”
“Reciprocals”	“If the activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with I”	
“Rationals”	“Ratios arising from the scale”	“If consistency were to be forced by obtaining n numerical values to span the matrix”
“If the elements being compared are closer together than indicated by the scale, one can use the scale 1.1, 1.2,,..... still finer. one can use an appropriate even finer refinement.”		

The different criteria considered for identifying the best combination of HRES were the cost of energy (LCOE \$), area requirement, battery usage, employment potential and GHG emissions. To develop the matrix table of weights for different criteria, a survey was carried out to get the opinion of experts comprising of senior officials from the township authority, a few faculties from prominent Indian universities with expertise in renewable energy and an official from Ministry of Renewable Energy, Government of India. The desirable results of the different criteria were lower cost of electricity, lesser area usage, lesser battery usage, higher employment potential and lesser GHG emissions. The lower cost of energy and lower area usage requirements were provided higher priority due to availability of very less area for HRES installation inside the campus. The lesser usage of battery indicated a higher availability and penetration of renewable energy resources and thus a more reliable system, Hence, battery usage was thus given a higher priority over employment potential and emission. The employment potential was a critical aspect as the experts wanted to reduce the operational costs without compromising with the social welfare perspective of higher local employment generation. Therefore, a higher employment generation was considered a desirable result but was given a lesser preference compared to other criteria. The emission was given the least priority as the major emissions obtained in the present form of carbon were from biofuels which are considered carbon neutral unlike conventional fuels (217). The decision matrix (216) obtained is presented in **Table 3.11** and the relative weights of the criteria (216) have been provided in **Table 3.12**.

Table 3.10 The details of the optimal configurations of different combinations

Combination	PV Array (kW)	Wind Turbine (kW)	Biogas Generator (kW)	Syngas Generator (kW)	Hydro- kinetic Turbine (kW)	Battery (kW)	Converter (kW)	NPC (\$ Million)	LCOE (\$/kWh)	Area Required (m ²)	Emissions (kgs/yr)	Employ ment Potential 25 years (persons)
PV Battery	4026	-	-	-	-	40000.8	750	18.57	0.357	32212	0	4.43
Wind Battery	-	9065	-	-	-	97500	2200	32.30	0.613	25944	0	10.89
Biogas Battery	-	-	-	-	-	-	-	-	-	-	-	-
Syngas Battery	-	-	-	-	-	-	-	-	-	-	-	-
Hydrokinetic Battery	-	-	-	-	-	-	-	-	-	-	-	-
PV Wind Battery	4290	1455	-	-	-	31986	750	16.2	0.308	33711	0	6.02
PV Biogas Battery	3300	-	132	-	-	29376	700	14.80	0.281	28833	990319	4.32
PV Syngas Battery	3234	-	-	150	-	27499.2	700	14.50	0.275	27036	1147940	20.01
PV Hydrokinetic Battery	1980	-	-	-	300	15624	450	9.58	0.182	16735	0	6.79
Wind Biogas Battery	-	9375	132	-	-	70000.8	1300	38.40	0.731	18334	524979	9.67
Wind Syngas Battery	-	9300	-	150	-	66249.6	1150	37.4	0.712	15445	609848	17.97
Wind Hydrokinetic Battery	-	5505	-	-	300	36960	650	22.7	0.432	8808	0	10.01
Biogas Syngas Battery	-	-	-	-	-	-	-	-	-	-	-	-
Biogas Hydrokinetic Battery	-	-	-	-	-	-	-	-	-	-	-	-
Syngas Hydrokinetic Battery	-	-	-	150	300	720000	300	232	4.40	32024	1442994	24.80
PV Wind Biogas Battery	4917	1695	132	-	-	16000.8	600	13.3	0.253	37194	667747	7.77
PV Wind Syngas Battery	4323	71	-	150	-	21686.4	700	13.7	0.261	33274	1069706	20.52
PV Wind Hydrokinetic Battery	2475	710	-	-	300	8644.8	600	8.34	0.159	20591	0	8.14
PV Biogas Syngas Battery	2706	-	132	150	-	14251.2	700	10.5	0.199	25182	2101760	19.19
PV Biogas Hydrokinetic Battery	1419	-	132	-	300	6499.2	400	6.64	0.126	14386	692227	6.47
PV Syngas Hydrokinetic Battery	1353	-	-	150	300	5500.8	450	6.64	0.126	13087	777409	17
Wind Biogas Syngas Battery	-	6140	132	150	-	50450.4	1250	20.2	0.384	16941	1251307	15.17
Wind Biogas Hydrokinetic Battery	-	3190	132	-	300	18139.2	550	13.7	0.261	8483	411136	7.88
Wind Syngas Hydrokinetic Battery	-	2815	-	150	300	16516.8	550	12.9	0.245	7015	478549	14.02
Biogas Syngas Hydrokinetic Battery	-	-	132	150	300	78124.8	150	30.3	0.577	6998	2027539	16.42
PV Wind Biogas Syngas Battery	2442	1100	132	150	-	10874.4	150	10.0	0.191	23235	1612104	15.08
PV Wind Biogas Hydrokinetic Battery	1188	355	132	-	300	4000.8	400	5.92	0.113	12994	560710	6.49
PV Wind Syngas Hydrokinetic Battery	1056	425	-	150	300	3249.6	400	5.94	0.113	10867	595808	14.49
PV Biogas Syngas Hydrokinetic Battery	891	-	132	150	300	600	450	5.19	0.099	11952	1116856	11.71
Wind Biogas Syngas Hydrokinetic Battery	-	1340	132	150	300	1999.2	150	6.53	0.124	4231	903649	10.20
PV Wind Biogas Syngas Hydrokinetic Battery	561	255	132	150	300	374.4	350	5.00	0.095	9121	995709	9.92

Table 3.11 Decision Matrix for the AHP analysis

Criteria	Emission	Employment Potential	Battery Usage	Area	LCOE
Emission	1	1/5	1/5	1/7	1/9
Employment Potential	5	1	1/3	1/2	1/5
Battery Usage	5	3	1	1/2	1/2
Area	7	2	2	1	1/2
COE	9	5	2	2	1

Table 3.12 Relative Weights of the criteria

Criteria	Emission	Employment Potential	Battery Usage	Area	LCOE
Weights	0.033975	0.103511	0.19294	0.251097	0.418476

The consistency ratio obtained for the weight matrix is .041 which was well below the desirable limit of 0.10 (216) which validates the consistency of the weights of different criteria. The normalized matrix values (216) along with the combined weights has been provided in **Table 3.13**.

Table 3.13 Normalised weight matrix for different combinations

Combination	Battery	LCOE	Area Required	Emissions	Employment Potential	Overall Weight
PV Battery	0.00936	0.266106	0.131349	0.178629	1	0.198612
Wind Battery	0.00384	0.154976	0.163082	0.439113	1	0.185972
Biogas Battery	-	-	-	-	-	-
Syngas Battery	-	-	-	-	-	-
Hydrokinetic Battery	-	-	-	-	-	-
PV Wind Battery	0.011705	0.308442	0.125508	0.242742	1	0.22195
PV Biogas Battery	0.012745	0.338078	0.146742	0.174194	0.000001	0.198814
PV Syngas Battery	0.013615	0.345455	0.156495	0.806855	0.000001	0.270005
PV Hydrokinetic Battery	0.023963	0.521978	0.252823	0.27379	1	0.348858
Wind Biogas Battery	0.005349	0.129959	0.230773	0.389919	0.000002	0.153724
Wind Syngas Battery	0.005651	0.133427	0.27394	0.724597	0.000002	0.200716
Wind Hydrokinetic Battery	0.01013	0.219907	0.480359	0.403629	1	0.290352
Biogas Syngas Battery	-	-	-	-	-	-
Biogas Hydrokinetic Battery	-	-	-	-	-	-
Syngas Hydrokinetic Battery	0.00052	0.021591	0.13212	1	0.000001	0.145821
PV Wind Biogas Battery	0.023399	0.375494	0.113755	0.313306	0.000001	0.222644
PV Wind Syngas Battery	0.017264	0.363985	0.127156	0.827419	0.000001	0.273226
PV Wind Hydrokinetic Battery	0.043309	0.597484	0.205478	0.328226	1	0.377934
PV Biogas Syngas Battery	0.026271	0.477387	0.168017	0.77379	0	0.327128
PV Biogas Hydrokinetic Battery	0.057607	0.753968	0.294105	0.260887	0.000001	0.427486
PV Syngas Hydrokinetic Battery	0.068063	0.753968	0.323298	0.685484	0.000001	0.480784
Wind Biogas Syngas Battery	0.007421	0.247396	0.249749	0.611694	0.000001	0.23099
Wind Biogas Hydrokinetic Battery	0.02064	0.363985	0.498762	0.317742	0.000002	0.314429
Wind Syngas Hydrokinetic Battery	0.022668	0.387755	0.603136	0.565323	0.000002	0.376603
Biogas Syngas Hydrokinetic Battery	0.004792	0.164645	0.604601	0.662097	0	0.290173
PV Wind Biogas Syngas Battery	0.034429	0.497382	0.182096	0.608065	0.000001	0.323451
PV Wind Biogas Hydrokinetic Battery	0.093581	0.840708	0.325612	0.261694	0.000002	0.478721
PV Wind Syngas Hydrokinetic Battery	0.115214	0.840708	0.389344	0.584274	0.000002	0.532288
PV Biogas Syngas Hydrokinetic Battery	0.624	0.959596	0.353999	0.472177	0.000001	0.659727
Wind Biogas Syngas Hydrokinetic Battery	0.187275	0.766129	1	0.41129	0.000001	0.65041
PV Wind Biogas Syngas Hydrokinetic Battery	1	1	0.463875	0.4	0.000001	0.769299

Based on the AHP analysis, Combination 31 comprising of PV-Wind-Biogas-Syngas- Hydrokinetic-Battery was found to be the best combination with an overall weight of 0.769 for the selected study area.

3.3.4 Details of the Best Combination

The details of Combination 31 have been discussed in the following sub-sections.

3.3.4.1 Cost Breakdown of NPC for the best combination

The details of the Net Present cost for the combination 31 have been provided in **Table 3.14**. Among the various components the hydrokinetic turbines had the highest capital and replacement costs while the biogas generators had the highest operational costs.

Table 3.14 Break down of NPC for Combination 31

Name of Component	Capital Cost (\$)	Operational Cost (\$)	Replacement Cost (\$)	Salvage Cost (\$)	Fuel Costs (\$)	Total Costs (\$)
Wind Turbine	254,235	115,234	108,534	-65,798	0.00	412,205
Biogas Generator	59796	1,118,934	45,171	-6077.58	0.00	1,217,823
Battery	33,818	23,499	106,461	-218.91	0.00	163,558
Converter	22,750	52,721	12,015	-2,617	0.00	84,870
Hydrokinetic Turbine	952,200	180,759	1,030,000	-164,291	0.00	1,998,668
Syn gas Generator	107895	470,425	15,657	-20,932	79,996	653,040
PV Array	263,126	211,262	0.00	0.00	0.00	474,388
System	1,693,820	2,172,834	1,317,838	-259,934	79,996	5,004,552

3.3.4.2 Annual Production Summary of Different renewable energy sources

The annual production summary of different renewable energy sources has been provided in **Table 3.15**. It was observed that the hydrokinetic turbines had the highest contribution while the syngas generator had the lowest contribution.

Table 3.15 Annual Production Details of different resources for combination 31

Component	Production (kWh/yr)	Percent
PV Array	862,136	21.8
Biogas Generator	483,261	12.23
Syn gas Generator	205366	5.2
Wind Turbines	340,883	8.63
Hydrokinetic Turbines	2,058,560	52.1
Total	3,950,206	100

3.3.5 Sensitivity Analysis

Sensitivity analysis of an HRES was necessary to comprehend the system behavior with changes in the availability and costs parameters of various renewable energy resources in the selected site area. The sensitivity analysis of the best combination, that is, combination 31 was carried out for variation in flow speed of river, the capital costs of the hydrokinetic turbines and interest rates and inflation rates and load demand. The reason for selection of these aspects were due to the fact that the speed of Teesta has been changing continuously owing to construction of several hydel power projects upstream. The hydrokinetic turbine is a relatively new technology and its prices are likely to come down in near future with implementation of Government policies for the same. The inflation and interest rates change very frequently in India. The biomass prices also change with increase or decrease of biomass availability. The variations in the load demand will help to understand the system behavior for smaller or larger townships within this region.

3.3.5.1 Effect of Inflation Rates, Interest Rates and Capital Costs of Hydrokinetic Turbines on the LCOE

Table 3.16 represents the effect of different inflation rates, interest rates and capital costs of hydrokinetic turbines on the Levelized cost of energy (LCOE). The least LCOE was observed at a nominal interest rate of 8% and expected inflation rate of 6.5% with the lowest hydrokinetic multiplier cost i.e. at 50 % of the present capital cost of the hydrokinetic turbine while the highest was observed for a nominal interest rate of 12% and expected inflation rate of 6.5 % at the present capital costs. At the current interest rate and inflation rate, the cost of energy reduced by about 9.5% when the capital cost of hydrokinetic turbines reduced by 50%.

Table 3.16 Effect of capital costs of hydrokinetic turbines, interest rate and inflation rate on the LCOE

Nominal Discount Rate	Expected Inflation Rate	Hydrokinetic Turbine Capital Cost Multiplier	\$ LCOE
8	3.5	0.5	0.0861
10	3.5	0.5	0.0905
12	3.5	0.5	0.0948
8	3.5	0.75	0.0907
10	3.5	0.75	0.0960
12	3.5	0.75	0.101
8	3.5	1	0.0952
10	3.5	1	0.101
12	3.5	1	0.108
8	5	0.5	0.0826
10	5	0.5	0.0871
12	5	0.5	0.0914
8	5	0.75	0.0865
10	5	0.75	0.0918
12	5	0.75	0.0971
8	5	1	0.0903
10	5	1	0.0965
12	5	1	0.101
8	6.5	0.5	0.0792
10	6.5	0.5	0.0836
12	6.5	0.5	0.0880
8	6.5	0.75	0.0825
10	6.5	0.75	0.0877
12	6.5	0.75	0.0929
8	6.5	1	0.0857
10	6.5	1	0.0917
12	6.5	1	0.0978

3.3.5.2 Effect of hydrokinetic flow speed on the LCOE and hydrokinetic penetration

Hydrokinetic flow speed was a variable in this analysis as the upcoming mega hydel power projects in the region may further reduce the flow speed of the Teesta River. At the same time, an untamed Teesta River in the absence of any hydel power projects may have a higher flow speed than the present speed. It has been observed in **Figure 3.11** that below average annual flow speeds of 1.5 m/s and beyond 3 m/s, the hydrokinetic electrical production reduced, resulting in higher costs of energy (LCOE). The lesser values of cost of electricity were obtained when the average annual flow speed was around 2.5 to 3 m/s.

3.3.5.3 Variation of the LCOE with load demand

The upcoming townships in the region may have a lesser or larger electrical demand than the considered township for this analysis. So, the effects of electrical demand on the LCOE were analyzed with maximum capacities of different components same as that of the present electrical demand. From **Figure 3.12**, it was observed that for various percentage of the present electrical load, the cost of electricity remains in the range of 0.092 \$/kWh to 0.1\$/kWh, but increased drastically when the electrical load increased by 25 % of the present load. The hydrokinetic electrical production also decreased drastically at 125% of the present electrical load.

3.3.5.4 Variation of LCOE with cost of syngas fuel

The HRES behavior in terms of LCOE for change in cost of biomass were also analyzed as the cost of biomass varies from region to region and may change further owing to change in demand. It was observed that the LCOE did not vary drastically with change in the cost of syngas fuel. This was due to the preference of cheaper resources over syngas as the cost of syngas fuel increased, which resulted in lesser electricity production from syngas generators as can be seen in **Figure 3.13**.

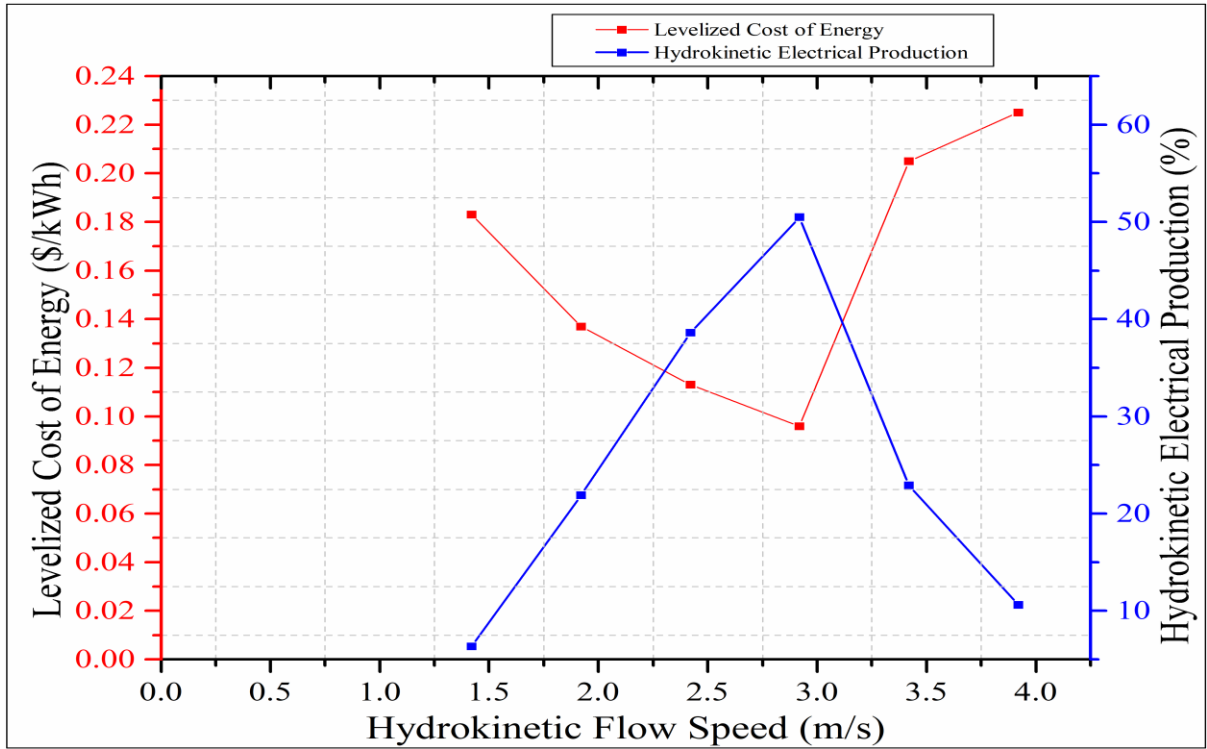


Figure 3.11 Sensitivity analysis for variation in Hydrokinetic flow speed

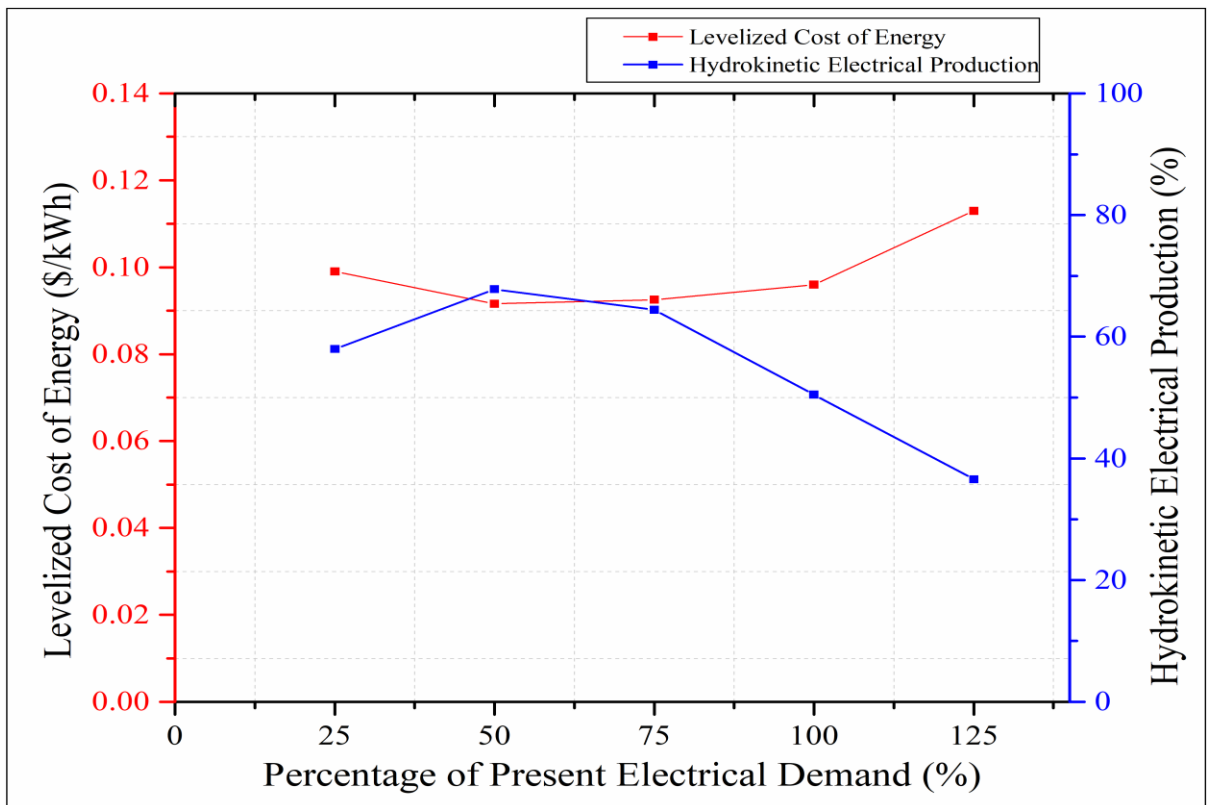


Figure 3.12 Sensitivity analysis for variations in electrical demand (%)

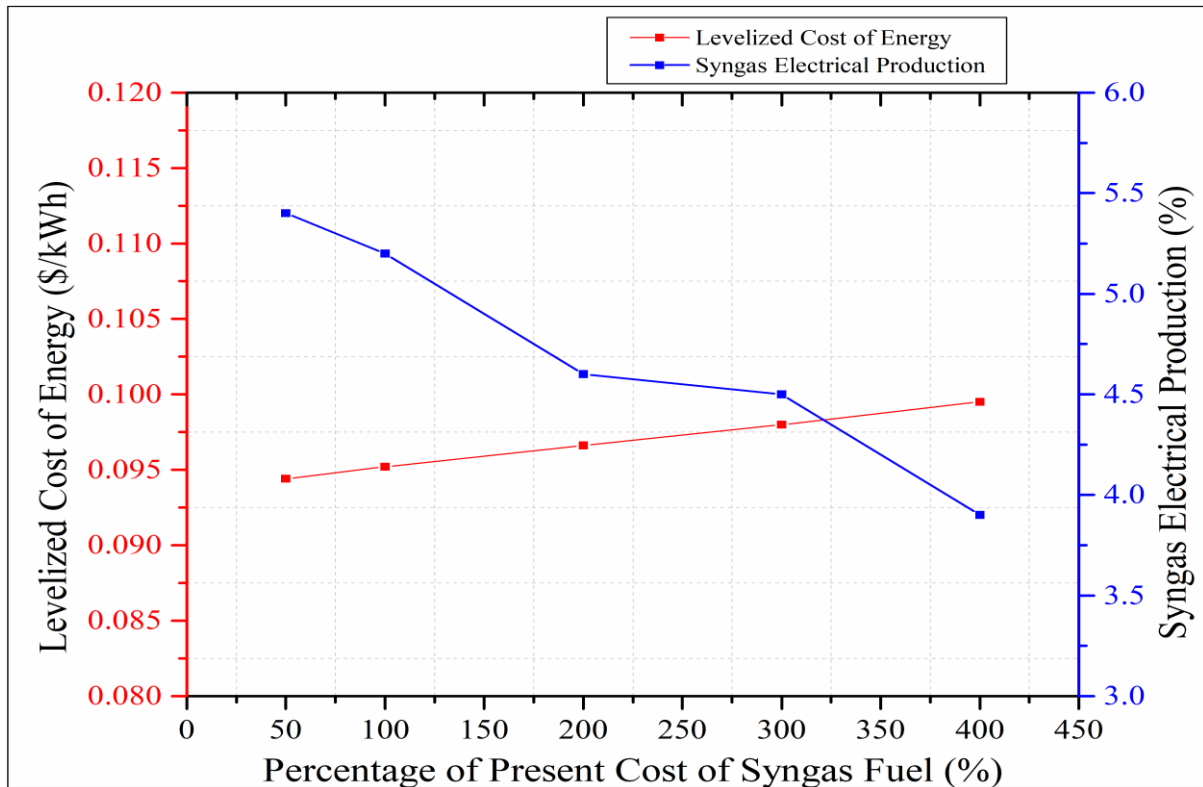


Figure 3.13 Sensitivity analysis for variations in cost of syngas fuel

3.4 Discussion

Out of the 31 combinations simulated in this analysis, 26 combinations managed to supply the electrical demand without capacity shortage. It was also observed that there was not a single winner for all the criteria considered. So, Analytical Hierarchy Process was utilized to identify the best combination in which cost of electricity and area usage were given higher priority. The PV-Wind-Biogas-Syngas-Hydrokinetic-Battery based HRES was identified as the best combination. For the best combination in this study, it was observed that the contribution of hydrokinetic energy was the highest (52%). Addition of hydrokinetic energy to PV-Wind-Biogas-Syngas-Battery (Combination 26) significantly brought down the LCOE which implied that hydrokinetic energy was the cheapest source. Based on sensitivity analysis, it was observed that the LCOE was on the lower side, when the inflation rates were higher and interest rates were lower and reduction of capital costs of hydrokinetic turbines also reduced the LCOE. The lesser values of cost of energy were obtained when the average annual hydrokinetic flow speed was around 2.5 to 3 m/s. This range of flow produced maximum power output from the hydrokinetic turbine as can be seen from Table 3.4 and thus the hydrokinetic energy contribution increased resulting in lesser cost of energy. With the limited contribution of syngas fuel towards the energy production (5.2%), the variations in the price of syngas fuel did not significantly impact the cost of energy. With the increase in electrical demand, the cost of energy increased as the contribution from hydrokinetic energy reduced, due to its limited availability.

A comparison of LCOE of the best system in this analysis with some other research works which have used four or more renewable energy resources in some other parts of India (1,2,97) showed that the LCOE depended greatly on the initial capital costs estimations, time period or year during which the costs have been considered, type of resources and availability of cheaper resources which is site specific. The LCOE of the best system in present work was much lower than the LCOE obtained in (97) due to different capital costs assumptions but in proximity to those obtained in (1,2) due to similar capital costs assumptions. Secondly, it was observed in this analysis that the LCOE decreased when number of renewable energy resources increased in an HRES which has been also observed in (1,2,97). However, the analysis in this work was based on location constraints and also all the possible combinations were analyzed for different conflicting criteria which has not been done in these literatures. As per IRENA report on renewable power costs generation (218), the capital costs and

levelized costs of energy have declined considerably between 2010 to 2018 and the costs are lesser in countries like India and China when compared to developed nations and European Union. Hence, best system identified in this analysis can have a totally different LCOE when realized in some other region of the world. In this study, the cheaper cost of electricity and lesser land usage were given higher priority over other criteria, However, with changes in the priority of criteria or in a different location with different priority, a different combination may become the best option.

3.4.1 Possibility of grid parity

The average central grid tariff (219) for the township has been obtained directly through the bills from the power station which has come to be \$1.05. A comparison of the LCOE of the best system with the grid price showed that the HRES has a high possibility of achieving grid parity if the system performs with minimal failure for the projected period of 25 years or with insignificant deviations from this analysis and with further reduction in capital cost of the system in future.

Chapter 4 Case Study 2: Modelling of an autonomous DES for electrification of a Grocery Shop

4.1 Introduction

It has been observed in Chapter 1, that the techno-economic investigations have been rarely conducted for market load independently in the world and especially not in India and in Sikkim. The demand profile for a market load demand is unique in India. Its daily span is generally longer than a typical school or office load demand but shorter than a residential load demand and design of a DES for such a load demand may yield unique results. Also, prominently used synthetic non-stochastic time series electrical load data generations solely based on interviews or assumptions, for techno-economic investigations in unelectrified and unreliable grid locations like India can vary significantly from the real load data (178,179) which can also impact the final microgrid design and economic outcomes. In this regard, few techniques and software (176,177,180,181) have been developed which can generate load data in good proximity of real load data by taking the stochastic variations into account. Based on these observations in this case-study, a techno-economic investigation was conducted for an off-grid PV-Wind-Battery based HRES for electrification of a grocery shop and the Levelized Cost of energy was determined along with the optimal size of the system.

Methodology

HOMER Pro Microgrid Analysis Tool has been utilized to execute the analysis. Initially, “Optimizer” has been used to identify the rough installation capacities or size of the system. After deducing the rough capacities, “Search Space” has been used to determine the exact capacities or exact size of the system based on market sizes available for installation. The requisite inputs for HOMER Pro are deliberated in the subsequent sections.

4.2 Identification of Site

Majhitar area of Sikkim, India (**Figure 3.2**) located at “27° 10.6’N latitude, 88° 31.7’E longitude” was considered as the sample site for the investigation as it has a continuously growing population and a considerable population concentration. The inhabitants of the location also have to face regular power outages for the entire year. The market sector of the location is constantly growing with several shops coming up. Out of a diversified market sector, grocery shops were considered for this investigation as these are one of the most important shops dealing in essential commodities and regularly opened for almost the entire year. A total of seventeen departmental shops were surveyed at random in the location and queries were made regarding appliance user behavior and monthly electricity bills and the one with the highest average monthly electricity bill was considered for this investigation.

4.3 Generation of Demand Profile for the Shop

Though the monthly electricity bills were available for the shop but they were not representative of the exact electrical demand as the power demand during power outages were compensated by diesel generators and the same was not recorded in any measuring device. Secondly, the hourly load profiles were difficult to capture directly from metered data. Thus, due to unavailability of real time series load data, RAMP was used to generate the load data (176) and profile. A survey was conducted via a questionnaire to collect the various input data for RAMP. The various inputs parameters required for RAMP include the power rating of a particular appliance, quantity of a particular appliance, total time of use of appliance in a day in hours (t_{max}), minimum time the appliance is kept on after switch-on event in minutes (t_{min}), percentage of total time of operation that the appliance is subject to random variability (t_{maxvar}) over a given period, number of functional windows within the day for the appliance (N_{wind}), starting time of each window ($t_{start,wind}$), ending time of each window ($t_{end,wind}$),

percentage of variability in the start and ending times of the windows ($t_{wind,var}$) over a given period. The details of the equipment used in the shop and a sample of input details necessary for the RAMP software have been provided in Table 4.1 and Table 4.2 respectively. After providing these input data, the number of days for which such data should be generated is needed to be provided and RAMP generates this data in .xls files in high resolution of minutes for those days.

4.4 Resource Availability

The resources considered for this investigation were solar and wind as the other resources namely biomass and hydrokinetic sources are limited by forests and river regulations (19,20) while the unpleasant odour of biogas (16) may not be desirable in a congested locality like a market place. The various resource potential data were directly imported via HOMER PRO from National Renewable Energy Laboratory (NREL), USA database. The site had a reasonably attractive solar energy potential with an average annual radiation of 4.74 kWh/m²/day. The site had higher clearness index during winter rising up to 0.640 in November which dipped down to 0.387 during rainy season in the month of July. But, the wind energy potential for this site was poor with an annual average of 2.29 m/s. The monthly wind speed was least in December with an average of 1.72 m/s and was highest in June and July with an average of 2.81 m/s. The temperature for the location was moderate more inclined towards the cooler side ranging between 5.26^oC and 18.4^oC with an annual average of 12.94 ^oC. The details of resource potential for the location have been depicted in **Figure 3.4**, **Figure 3.5** and **Figure 3.6** respectively (Chapter 3).

Table 4.1 Details of Appliances Used in the Grocery Shop

Appliance Name	Appliance Code	Rated Power of the Appliance (Watt)	Quantity
LED Bulb1	A1	7	6
LED Bulb2	A2	9	6
Ceiling Fan	A3	70	1
Table Fan	A4 (occasional use)	45	1
Weighing Machine Charger	A5 (occasional use)	12	1
Glass Door Refrigerator1	A6	195	1
Glass Door Refrigerator2	A7	195	1
Deep Freezer	A8	290	1
Debit/Credit Card Machine	A9(occasional use)	6	1
Desktop Computer	A10	230	1
CCTV Camera	A11	9	4

Table 4.2 Details of inputs required for RAMP software for the month of June

Appliance Code	t_{max}	t_{min}	t_{maxvar}	N_{wind}	$t_{start,wind}$	$t_{end,wind}$	$t_{wind,var}$
A1	13	15	10%	1	8:00 AM	9:00 PM	10%
A2	4	15	15%	1	5:00 PM	9:00 PM	20%
A3	13	15	15%	1	8:00 AM	9:00 PM	20%
A4 (occasional use)	4	15	30%	1	8:00 AM	9:00 PM	30%
A5 (occasional use)	2	30	30%	1	8:00 AM	9:00 PM	35%
A6	13	60	10%	1	8:00 AM	9:00 PM	10%
A7	24	60	10%	1	0:00 AM	0:00 AM	0%
A8	24	60	10%	1	0:00 AM	0:00 AM	0%
A9 (occasional use)	2	30	30%	1	8:00 AM	9:00 PM	35%
A10	13	30	35%	1	9:00 AM	9:00 PM	10%
A11	13	30	30%	1	9:00 AM	9:00 PM	10%

4.5 System Design and Economic Modelling

The design of various system components namely solar panels was done using Eq. 2.1-Eq. 2.2, wind turbines using Eq.2.3-Eq. 2.4, battery using Eq. 2.11 – Eq.2.17 and converter using Eq. 2.18-Eq. 2.20 and economic modelling was done using Eq.2.21- Eq. 2.24.

4.6 Technical and Economic Specifications of Various Equipment of the HRES

The technical and economic specifications of the various equipment were taken from local market through quotations and provided in **Table 4.3** and **Table 4.4**. The average inflation rate was considered to be 3.5 % and discount rate was considered to be 8%. And the project lifetime was considered to be 25 years.

Table 4.3 Technical Specification of Component

Component	Parameter	Value
PV System (46)	Rated Capacity of each PV module(E_{RPV})	330 W
	Derating Factor(g_{PV})	88 %
	Nominal Operating Cell Temperature($T_{c,NOCT}$)	44°C
	Temperature Co-efficient(β_p)	-0.41 %/°C
	Efficiency at Standard Conditions(η_c)	17.01 %
Wind System (47)	Rated Power	1 kW
	Hub Height	10 m
Battery (46)	Rated Capacity	1.8 kWh
	Round Trip Efficiency	85 %
	Least State of Charge	20%
	Rectifier Efficiency	98.7 %
Converter (46)	Rated Capacity	600 Watt
	Inverter Efficiency	98.3%
	Rectifier Efficiency	98.7 %

Table 4.4 Economic Specification of Component

Component Details	Capital Costs (USD)	Replacement Costs (USD)	Operation & Maintenance Costs (USD)	Component Life
PV System (46,48)	459/kW	459/kW	10/year	25 yrs
Wind System (47,48)	997 /kW	997 /kW	30/year	20 yrs
Battery (46,48)	\$216.78/battery	160.47/battery	5/year	5 yrs
Converter (46,48)	65/kW	65/kW	10/year	15 yrs

4.7 Results

4.7.1 Generation of Load Data Using RAMP

The high-resolution load data generated through RAMP for all months were imported into HOMER Pro to generate the final load data for the entire year. A sample load profile generated by RAMP has been provided in **Figure 4.1** and the load profile generated for the entire year by HOMER PRO has been provided in **Figure 4.2**. The average load per day for the entire year was 5.26 kWh with an average load of 0.22 kW and a peak load of 1.03 kW. The load factor for the demand was 0.21. The day-to-day random variation was found to be 9.24% while the random variation on a time step basis of a minute was found to be 95.71%. The peak month was found to be April. The time series validation of the load profile was not possible due to lack of smart meters in the location.

4.7.2 HOMER PRO Simulation Results

Simulations for all the three possible combinations of the HRES have been conducted in HOMER Pro Microgrid Tool using the collected economic and technical database on a time step of one minute for deduction of net present cost (NPC) in US Dollars and Levelized Cost of Electricity (LCOE). The corresponding results obtained have been provided and discussed in following sub-sections.

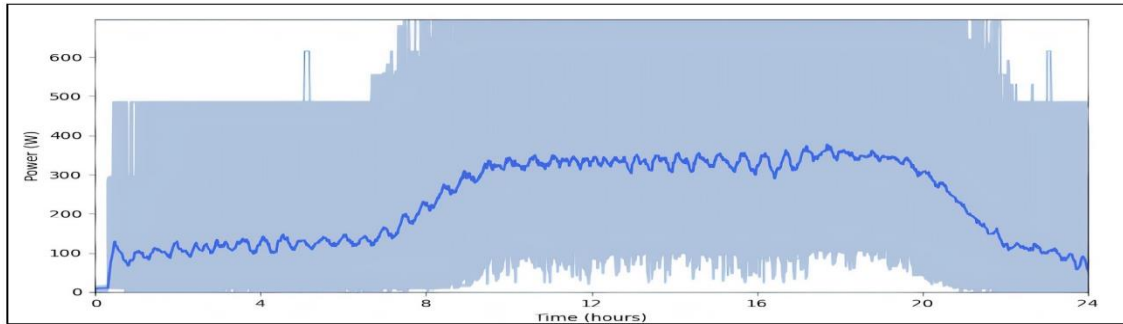


Figure 4.1 Load Profile Generated for the month of June through RAMP for the grocery shop

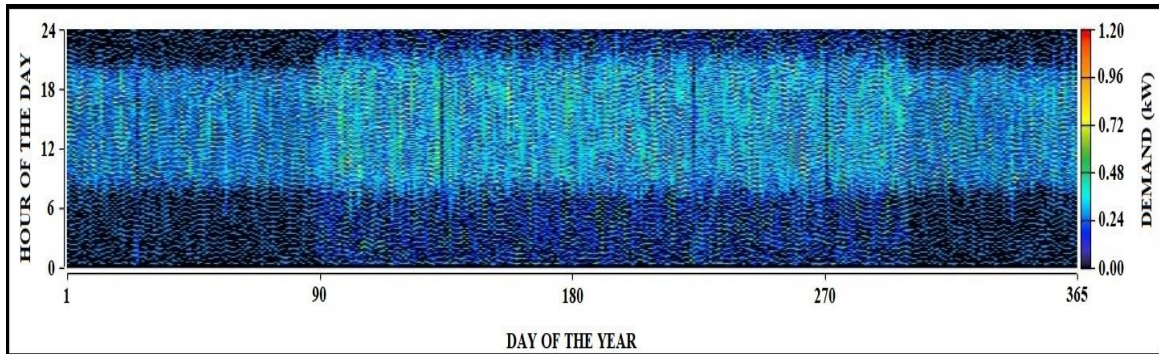


Figure 4.2 Load Profile Generated through HOMER for the entire year

4.7.2.1 Combination 1: PV-Battery System

The optimum system configuration for this combination required 13 PV modules of 330 W each, 9 batteries of 12 V, 150 Ah each and 2 converters of 600 Watt each. The NPC of the system was 7901 US \$ with the LCOE as 0.311 \$/kWh. The breakup of the total component cost of the system has been provided in **Table 4.5**.

Table 4.5 Break up of total cost of PV-Battery System

Component	Capital Cost (\$)	Replacement Cost (\$)	Operation and Maintenance Cost (\$)	Fuel Cost (\$)	Salvage Cost (\$)	Total Cost (\$)
Battery	1002.90	2921.63	903.80	0	120.99	4707.34
Converter	168.90	71.72	180.76	0	43.48	377.00
Solar PV Panel	2120.58	0	695.92	0	0	2816.50
Total System	3291.48	2993.35	1780.48	0	164.47	7900.84

4.7.2.2 Combination 2: Wind-Battery System

The optimum system configuration required 23 wind turbines of 1 kW each, 121 batteries of 12 Volts (V), 150 Ampere-hour (Ah) each and 7 converters of 600 watt each. The NPC was 93641 US \$ with the LCOE as 3.24 \$/kWh. The breakup of the total component cost of the system has been provided in **Table 4.6**.

Table 4.6 Break up of total cost of Wind-Battery System

Component	Capital Cost (\$)	Replacement Cost (\$)	Operation and Maintenance Cost (\$)	Fuel Cost (\$)	Salvage Cost (\$)	Total Cost (\$)
Battery	20225.15	0.00	18226.53	0	1847.07	36604.61
Converter	588.00	251.02	632.66	0	152.18	1319.50
Wind Turbine	22931.00	9789.37	12190.06	0	5810.49	39099.96
Total System	43744.15	10040.39	31049.25	0	7809.73	77024.07

4.7.2.3 Combination 3: PV-Wind-Battery System

The optimum system configuration required 14 PV modules of 330 W each, 1 wind turbine, 7 batteries of 12 V, 150 Ah and 2 converters of 600 watt each. The NPC was 10505 US \$ with the LCOE as 0.408 \$/kWh. The breakup of the total component cost of the system has been provided in **Table 4.7**.

Table 4.7 Break up of total cost of PV-Wind-Battery System

Component	Capital Cost (\$)	Replacement Cost (\$)	Operation and Maintenance Cost (\$)	Fuel Cost (\$)	Salvage Cost (\$)	Total Cost (\$)
Battery	1170.05	2454.93	1054.43	0	63.95	4615.46
Converter	168.00	71.72	180.76	0	43.48	377.00
Solar PV Panel	1666.17	0	546.80	0	0	2212.97
Wind Turbine	997	425.62	2121.01	0	244.23	3299.40
Total System	4001.22	2952.28	3902.99	0	351.65	10504.83

4.7.2.4 The best combination for the grocery store

Out of the three systems the best combination for the grocery store was found to be PV-Battery system with an LCOE of 0.273 \$/kWh. In comparison to central grid however, none of the system was found to be competitive as the cost per unit for grid was found to be 0.105 \$/kWh which was much lesser than any of the three combinations.

4.8 Sensitivity Analysis

To comprehend the system performance for this type of load profile on a broader perspective, a sensitivity analysis was conducted for the PV-battery configuration across different climatic conditions of India. The distribution of system LCOE, the average annual global solar radiation ranges (240), the average annual temperature ranges (242) and the corresponding sensitivity variables for radiation and temperature across various states and union territories of India is shown in **Figure 4.3** (Abbreviations at **Table 5.10**). The empty spaces indicate that the absence of any region in that combination of radiation and temperature range. Localities in Arunachal Pradesh (AP) have the highest LCOE (0.358 \$/kWh) while localities in Jammu and Kashmir (JK) and Ladak have the lowest (0.292 \$/kWh).

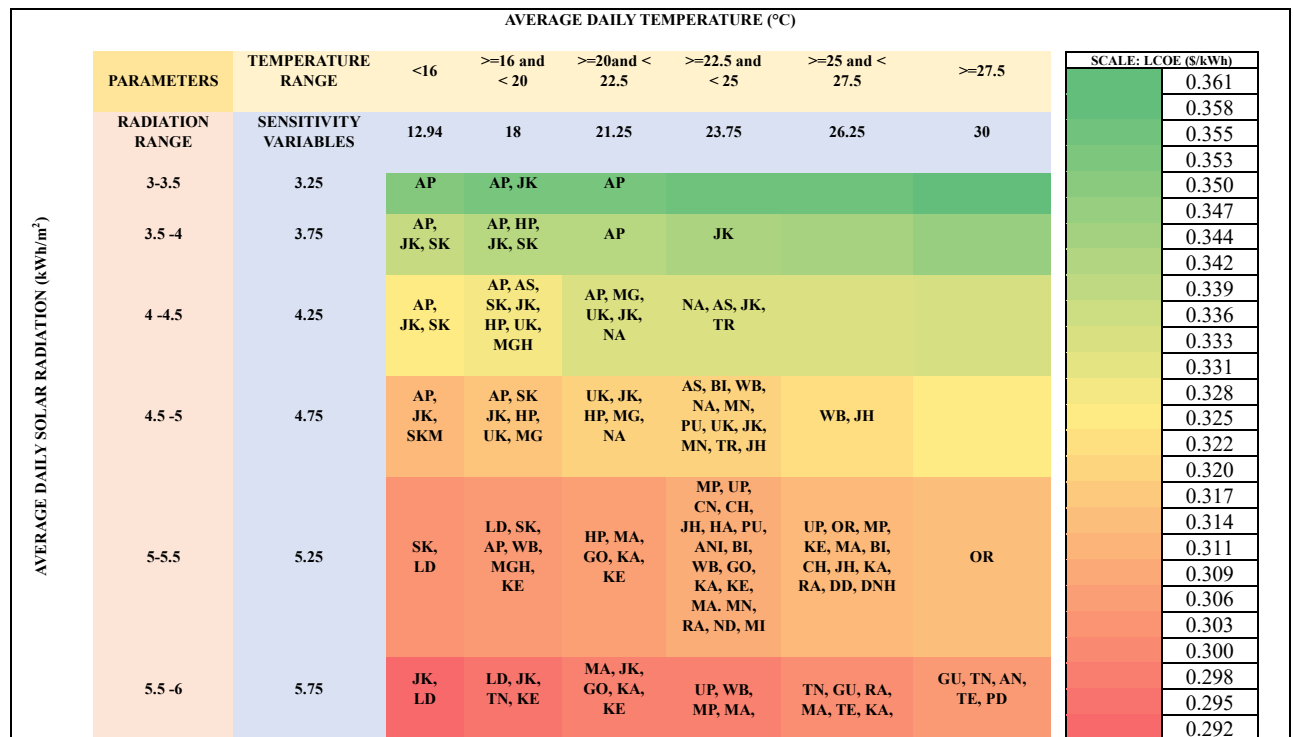




Figure 4.3 LCOE for the system for the grocery shop load profile across different locations of India

4.9 Discussion

Out of the 3 combinations, wind-battery combination had the highest LCOE in the location for grocery shop while PV-battery combination had the least LCOE, similar to the results obtained for academic township case-study conducted in Chapter 3. The LCOE of the PV-battery combination was higher in the present case-study for the grocery shop than the LCOE for PV-battery configuration in Chapter 3 for the academic township indicating a possible impact of the load demand profile. The high LCOE of wind-based systems eliminated its viability and possible use in the location while the relatively competitive costs of PV-based system make it a promising standalone prospect in the location for other type of load demands apart from the hydrokinetic energy. In this case-study, the spatial (area) feasibility of the system was not investigated as all the grocery stores were located at the ground floor of multi-storeyed buildings with limited space in front for installation of any such system while the rooftop area available was shared between residences staying in the floors above the grocery stores and the store itself which complicated the area requirement consideration of the system for these stores. This prospect has been investigated in detail in the next chapter for the residential sector. The LCOE of the PV-battery configuration ranged between 0.292 \$/kWh to 0.358 \$/kWh across different climating conditions for the grocery shop load profile which is higher than the LCOE for academic township with Sikkim being a considerably favourable location for the configuration.

Chapter 5 Case Study 3. Modelling of an autonomous roof-top PV nanogrid system for electrification of residential demand.

5.1 Introduction

In Chapter 3, the viability investigations of DESs were conducted for an academic township load profile comprising of amalgamation of residential load, academic load and public utility load like grocery shop while in Chapter 4, the investigation was conducted for an independent load profile namely the grocery shop load profile. In this chapter, the investigation has been extended to residential load profile.

In modern era of energy self-sufficiency and its personal preference, an off-grid DES or a nanogrid for private use in a single household or among limited number of households poses a promising futuristic prospect. However, several critical aspects need investigation to realize its viability in residential sector. Despite Sikkim's copious accessibility of various renewable energy sources (RESs) (21–24), the constraints associated with different renewable energy resources as observed in Chapter 3 and Chapter 4 provide a promising prospect for off-grid rooftop photovoltaic (PV) nanogrids in this region. Moreover, Ministry of New and Renewable Energy (MNRE) under Government of India (GOI) promotes solar energy via various subsidy schemes in this region (21,220). The main issues arising for an off-grid PV nanogrid are, its cost competitiveness with the grid and its space feasibility, that is, whether the roof top space available per household is enough for installation of an autonomous PV nanogrid that can reliably meet the electrical demand of that household. It is also important to recognize the type of buildings which can feasibly install such nanogrids and the impact of occupancy behaviour of residential end-users (221–227) either individual or grouped households on the nanogrid configuration, costs and performance prior to adoption in Sikkim or any other part of the country. So, a techno-economic-space feasibility investigation is necessary for such concerns.

In terms of roof-top area requirements for PV panels, most investigations have analysed the rooftop area potential for PV installation (228–236) through Geographical Information Systems (GIS) techniques. However, the available rooftop area particularly in a multi-storey building is likely to be divided per apartment/house per floor if a household decides to install a private nanogrid and such an area cannot be determined directly by GIS-based approaches (**Figure 5.4**). Also, synthetic non-stochastic time series electrical load data generations solely based on interviews or assumptions, for techno-economic investigations in unelectrified and unreliable grid locations like India can be replaced by use of software like RAMP for generation of more realistic load profiles.

Based on these observations, the objectives of this work are: (i) to conduct a techno-economic investigation by designing an off-grid rooftop PV nanogrid system with battery back-up for the residential sector of a cosmopolitan urban locality with unreliable electricity in the North-Eastern Himalayan state of Sikkim, India (ii) to generate stochastic load profiles necessary for investigation in proximity of real loads for different types of end-users existing in the location to understand their impact on the system configuration and the costs (iii) to investigate the feasibility of the PV nanogrids in terms of rooftop area availability (iv) to identify correlations between occupancy behaviour and output parameters of the designed nanogrid system (v) to determine the optimum subsidy for the nanogrid for the present location for its competitiveness with existing grid tariff (vi) to perform sensitivity analysis for the nanogrid with the generic load profile created by this investigation over different uncertain input parameters varying across India to have a broader perspective of this investigation.

5.2 Methodology

The methodology for this investigation (**Figure 5.1**) is detailed in the following sub-sections:

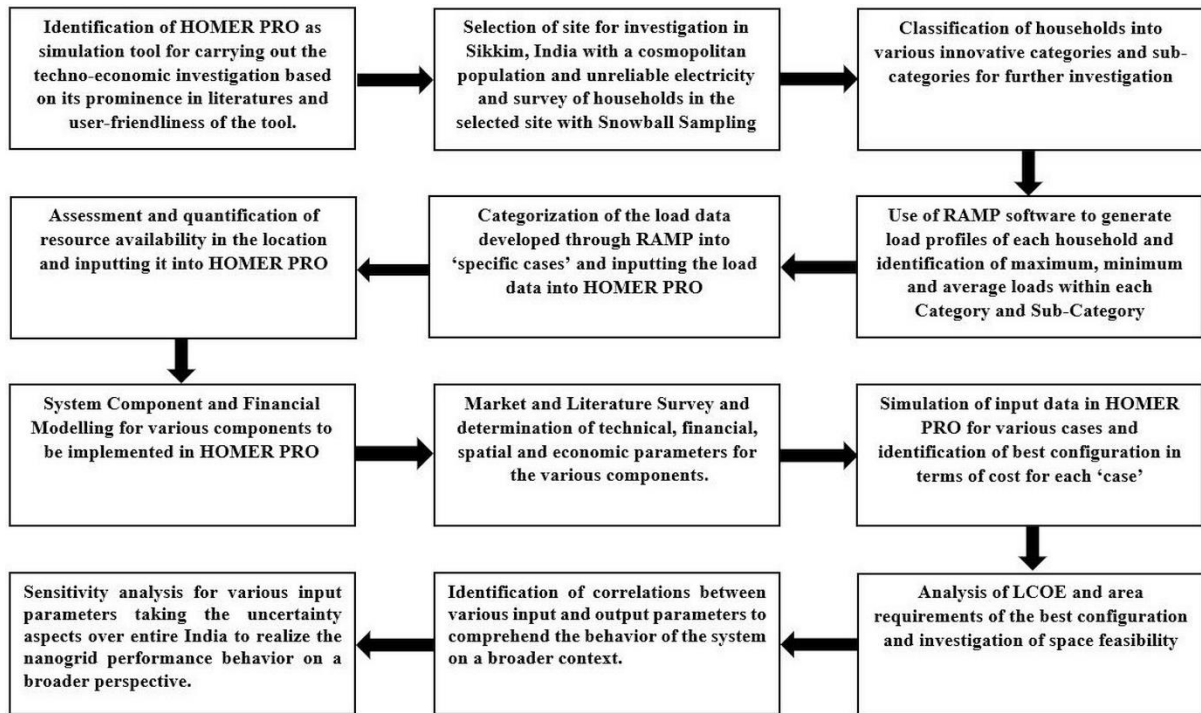


Figure 5.1 Flow chart of the methodology used in this investigation

5.2.1 Selection of Simulation Tool and Location

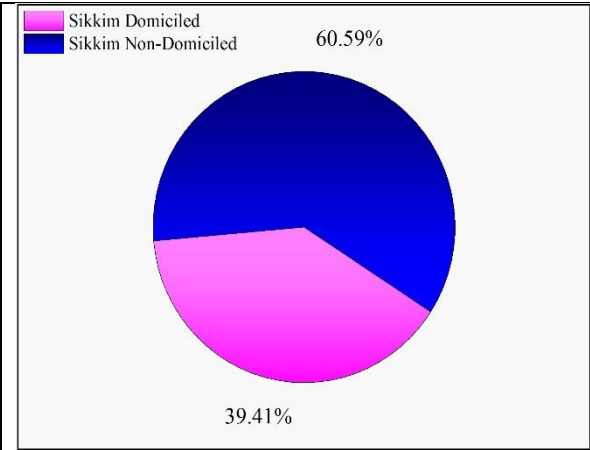
HOMER Pro Microgrid Analysis Tool has been used for this investigation. For this analysis, the entire Rangpo town under Pakyong district (previously East Sikkim) of Sikkim, India has been selected (Figure 3.2, Chapter 3)

5.2.2 Sampling Technique for generation of load profile

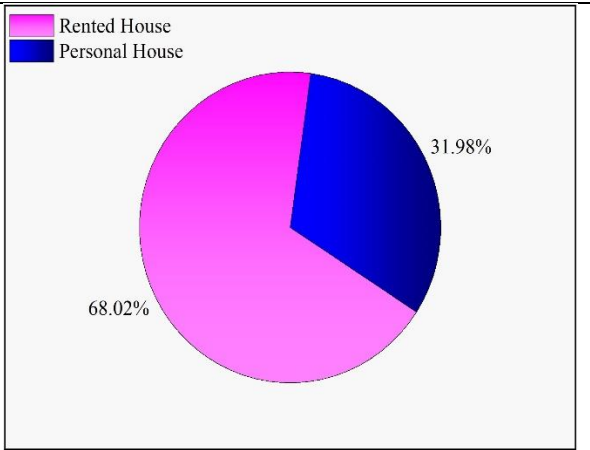
Due to complexities of data requirements and uncertainty of the exact population count, snowball sampling (237) was used to conduct a questionnaire-based survey (238) for collecting the data necessary for generation of load profile. The technique is very convenient in terms of cost and time effectiveness but is prone to sampling bias due to over-interactions with similar groups of people. To reduce the biasness, an attempt was made via interviews to recruit individuals with better and diverse social networks at specific junctions of survey like bank managers, private canteen and restaurant owners etc in the region who generally maintain cordial relations with their regular and reliable customers and also deal with a diversified group of prominent grocery store owners, doctors, fruit, diary, meat and vegetable vendors, bank people.

The survey consisted of an initial survey and a deep survey. A total of 417 telephonic calls were attempted to get the first 300 responses for the initial survey. Key restrictions were set prior to deep surveying. Due to complexity of collection of data and time requirements, a total of 269 households were visited physically for deep survey with a printed questionnaire and the answers were collected, after the initial survey. The details of the initial and deep questionnaire are provided in Table 5.1 and Table 5.2.

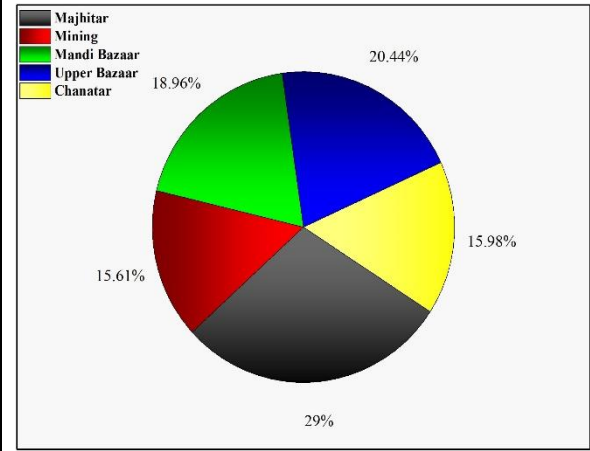
The diversity of the surveyed households in terms of demographics, wards, house ownership, roof type, power backup types, building types, number of dwelling rooms and appliance ownership classifications, presented in Figure 5.2 and Figure 5.3, clearly depicts the cosmopolitan nature of the region with a sundry user behaviour.



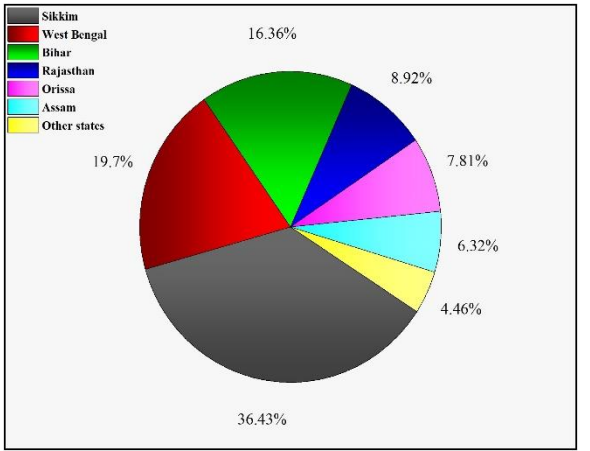
Details of Domicile



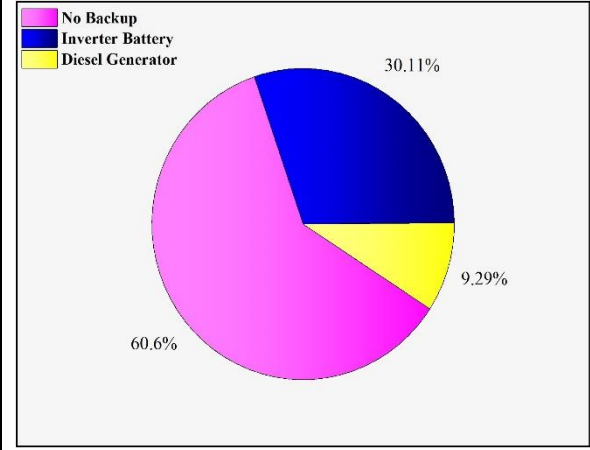
Details of Rented and Personal Houses



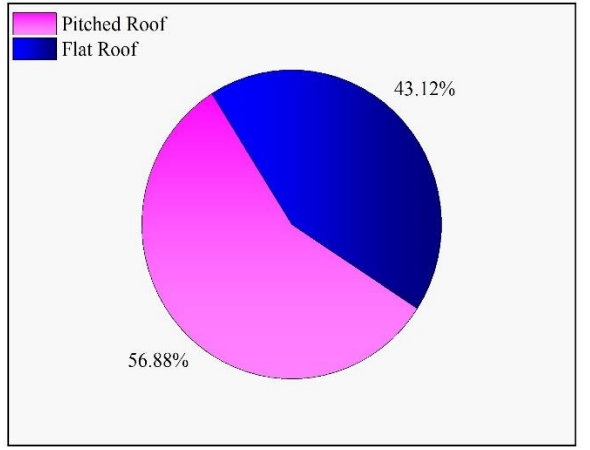
Details of Wards of Households



Details of State Domicile/Ethnicity



Details of Power Backup of Households



Details of Roof type

Figure 5.2 Various Details of the Surveyed households

Table 5.1 Questionnaire for Survey

OFF-GRID ROOFTOP SOLAR PANEL INSTALLATION FEASIBILITY SURVEY QUESTIONNAIRE											
PRELIMINARY SURVEY QUESTIONNAIRE AND REQUIRED RESPONSES FOR DEEP SURVEY (TELEPHONIC)											
1. Is the household located in the Rangpo suburb area?									Yes		
2. Is the household having any agricultural, commercial or industrial electrical utility source in their house in the Rangpo area?									No		
3. Is the family/household residing in their present house/location for a minimum of one year?									Yes		
4. Does the household members generally reside in their house for at least 9 months in a year (excluding vacations/official tours etc)									Yes		
DEEP SURVEY QUESTIONNAIRE (THROUGH FACE-TO-FACE INTERVIEWS AND DOOR-TO-DOOR VISITS)											
1. Name of the contact person/respondent: (Only collected for any future communications regarding the survey)					2. Contact Number: (Only collected for any future communications regarding the survey)						
3. State Domicile of the household:				4. Ethnicity of the household:							
5. Location of the household (Ward):				6. Whether the present house/apartment is rented or owned?			Rented	Owned			
7. If rented, then details of the owner				Name:			Contact Number:				
8. Total Number of persons in the household/house:			9. Annual Income of the household:			10. Smart meter availability?		Yes	No		
11. Number of males/females/children in the household:			12. Are Electricity bills for all the months of a year available?				Yes	No			
13. Number of persons in the house with occupation:					14. Number of persons in the house without an occupation:						
15. Timing of occupation of the household:		General Shifts (8 AM- 8 PM)			Shift Changes (Weekly)		Night Shifts only		Other _____		
16. Number of persons staying in the house generally throughout the day during weekdays? (More than 20 hours)							0	At least one			
17. Name of three-four persons/households in the Rangpo area who can be contacted on the basis of the current household's reference (Preferably at least one person in a different occupation/post/ job designation than the current household's occupation or in occupations involving more diverse interactions e.g. doctors, shopkeepers etc.)											
Sl. No.	Name				Contact Number				Occupation		
1											
2											
3											
4											
18. Floor area or Plinth area of the apartment/ house (To be measured by the surveyor if the household or the apartment owner does not know it)											
19. Type of energy meter in the house:			Smart	Conventional		20. Electricity bill availability for 12 months of a year:			Yes	No	
21. What is the frequency of power outages in the house?				Daily		Often		Rarely		Never	
22. Back up device used by the household during power outages?				Diesel Generator		Battery		Other	None	Not applicable	
23. Number of dwelling rooms in the house (Ignore the count of balconies, kitchen, toilets as separate rooms):											
24. Number of kitchens:			25. Number of lavatories/bathrooms:				26. Number of balconies:				
27. Type of building:		Semi-detached house	Detached house	Multi-storey building/ Apartment			28. For multi-storey buildings, number of storey:				
29. Type of roof:		Pitched	Flat	Other	30. For flat roof buildings, is the rooftop accessible to all the apartment owners: (To be answered by apartment owners if the rented households do not know)				Yes	No	
31. For flat roof buildings, approximate idea about how much roof area is free without any hindrances for panel installation: (To be visited by the surveyor if the respondent or the apartment owner is not able to answer)						< 30 %	30%-50%	50%-70%	>70%		

Table 5.2 RAMP Data Questionnaire

Demand Data for: Weekdays / Weekends											
SN	Appliance Name	Frequency of Use	Rated Power of The appliance	Quantity	Maximum time of use of appliance	Minimum time for which the appliance remains on	Day-to-Day Variations in maximum time of use	Number of functional windows	Exact duration of functional windows	Day-to-day variations in starting time and ending time of functional windows	Months with similar usage pattern
1	Fluorescent Tube light										
2	Refrigerator										
3	LED Bulb										
4	Ceiling Fan										
5	Exhaust Fan										
7	Television										
8	Set Top Box										
9	Washing Machine										
10	Vacuum Cleaner										
11	Laptop										
12	Microwave Oven										
15	Mixer Grinder										
16	Water Purifier										
17	Iron										
18	Water Pump										
19											
20											
21											
22											
23											
24											
25											

Day-to -day variations in percentages-Almost same (5-10%), Varies a little (15-20%), Varies a lot (30-35%), Quite Discrete/No pattern (35-50%)

5.2.3 Classification of households into Categories

Prior to generation of load profiles, the sampled households (houses) were classified according to the number of dwelling rooms (living rooms and bed rooms) available in the house, since the demand load, a critical input parameter of this investigation shows strong correlations with the number of dwelling rooms and dwelling area (221–224). To limit the classification to few categories, the count of non-dwelling rooms like kitchen, lavatories, balconies etc. were neglected. The households were further divided into three Sub-Categories under each Category, based on the occupants’ duration of stay at their houses during weekdays as this period also led to dominant use of electrical appliances (Table 5.3).

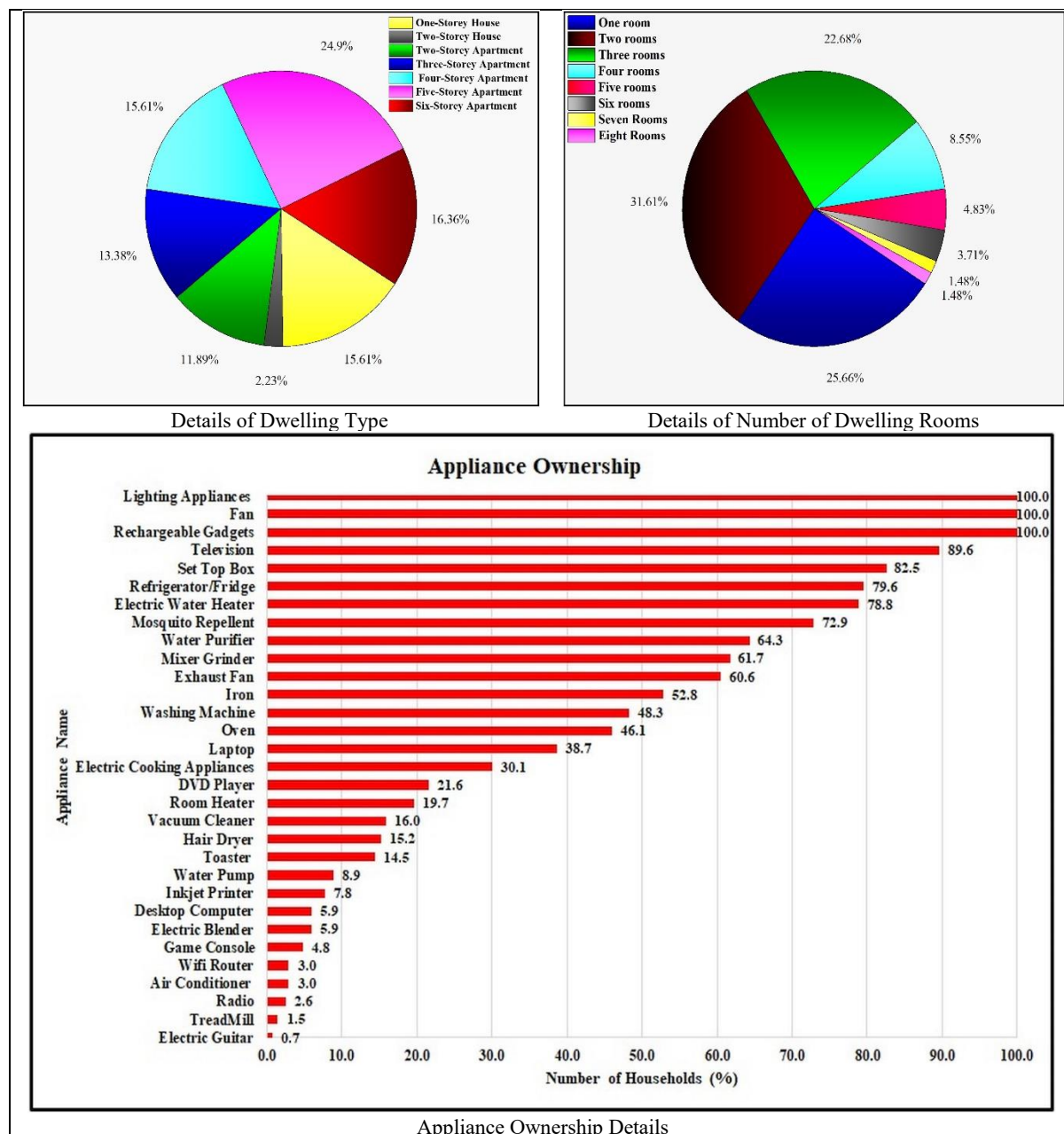


Figure 5.3 Various Technical Details of the surveyed households necessary for the investigation

5.2.4 Modelling of Load Data

Due to persistent unreliable electricity and unavailability of smart meters during the survey period of 2019-2021 in the location, “Remote-Areas Multi-energy systems load Profiles” (RAMP) software was used to generate load data for the location. A sample input data file for the same is

presented in **Table 5.4**. Samples of load profiles produced by RAMP for three sub-categories for April month (Case 15, 12 and 18) are presented in **Figure 5.5(a)-Figure 5.5(c)** where the variations in load profiles is clearly noticeable during the inoccupancy periods as per the “conditions” provided in **Table 5.3**. Further, demand load was lower during 12 AM-6 PM for every Sub-Category, due to inactivity. After load data generation for every household via RAMP, the household with the highest and the lowest monthly load were identified within each Sub-Category of a Category to fit into Criteria 1 and 2 respectively, while Criteria 3 considered the average of all monthly loads in a Sub-Category of a Category. These three ‘Criteria’ were framed to provide a comprehensive perspective of the possible impacts of the end-use behaviour on the outcomes in terms of maximum, minimum, average, individual and grouped load demand. The ‘Categories’, ‘Sub-Categories’ and ‘Criteria’ details are provided in **Table 5.3**.

Table 5.3 Details of main categories, sub-categories and criteria considered for this investigation

Category	Condition (Number of Dwelling Rooms)
Category 1	One Room
Category 2	Two Room
Category 3	Three Room
Category 4	Four Rooms
Category 5	Five Rooms
Category 6	Six Rooms
Category 7	Seven Rooms
Category 8	Eight Rooms
Sub-Category	Condition
Sub Category 1	The household (house) generally has a minimum period of about 6 hours during day time (6 AM-6 PM) on weekdays with no one available in the house resulting in lower load demand during that period of the day. (Observed among employees working in general shifts, shopkeepers, students etc.) (Fig. 5.5(b), 5.5(e))
Sub Category 2	The household (house) has a minimum duration of unavailability of residents in the house for 6 hours which shifted among 6 AM-2 PM, 2 PM-10 PM and 10 PM-6 AM on a week-to-week basis on weekdays for the entire year resulting in lower load demand during that period of the day. (Observed among industrial employees, journalists, police employees, security personals etc.) (Fig. 5.5(a), 5.5(d))
Sub Category 3	The household has some one always staying at home for the entire day on weekdays resulting in more uniform load profile throughout the day. (Observed among households with home makers, old retired personals, households having permanent caretakers and baby sitters, work from home personals.) (Fig. 5.5(c), 5.5(f))
Criteria	Condition
Criteria 1	Household with the Minimum Average Load (Minimum Monthly Average Load)
Criteria 2	Household with the Maximum Average Load (Maximum Monthly Average Load)
Criteria 3	Average of daily loads of all the households under the Sub-Category of that Category

Each Criteria under a Sub-Category of a Category has been considered as a Case for investigation. In addition, the Category Demand Averages, Sub-Category Demand Average and Average Demand of all the surveyed houses were considered for further investigation. Thus, 57 cases were considered for investigation (**Table 5.8**). The distribution of the various Categories and Sub-Categories along different “Types” of buildings along with the average base (plinth) area span is provided in **Table 5.5**. The Criteria Load generated by RAMP was imported to HOMER PRO for further simulation. Samples of annual load profile generated by HOMER Pro for Cases 15, 12 and 18 are presented in **Figure 5.5(d)-Figure 5.5(f)** respectively. **Figure 5.5(g)** represents the annual load profile for Category 2 per household which was the amalgamated profile of all the individual households or Sub-Categories under Category 2 (Case 20). It was the typical load profile/household for a microgrid or nanogrid shared among all the households of Category 2. The RAMP Codes along with the load profiles generated for HOMER PRO are available at (239).

Table 5.4 Input parameters for RAMP for weekdays in the month of April for Case 1

Appliance Name	Frequency of Use	P_{rated} (Watt)	Quantity	t_{max}	t_{min}	t_{maxvar}	N_{wind}	$t_{start,wind}$	$t_{end,wind}$	$t_{wind,var}$
Fluorescent Tube light	Occasional	55	4	120-420	15	15%	2	5:00 AM (W1) 6:00 PM (W2)	7:00 AM (W1) 12:00 AM (W2)	30 %
Refrigerator	Regular	200 (Power Cycle)	1	1440	720	10%	1	12:00 AM	12:00 PM	10%
LED Bulb	Regular	5	2	60	3	20%	2	5:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 12:00 AM (W2)	20 %
Hair Timmer Charger	Occasional	5	1	480	30	30%	1	6:00 PM	12:00 AM	30 %
Inkjet Printer	Occasional	1000	1	30	15	15%	1	7:00 PM	9:00 PM	10%
Ceiling Fan	Regular	70	2	420-720	15	15%	2	6:00 PM (W1) 12:00 AM (W2)	12:00 AM(W1) 8:45 AM (W2)	20%
Exhaust Fan	Regular	40	1	180	15	15%	2	7:00 PM (W1) 7:00 AM (W2)	10:00 PM (W1) 8:45 AM (W2)	20%
Kitchen Tube light	Regular	40	1	240	15	15%	2	6:00 AM (W2) 7:00 PM (W1)	8:45 AM (W2) 11:00 PM (W1)	20%
Induction Cooktop	Regular	2000	1	150	15	15%	2	6:00 AM (W1) 6:00 PM (W2) 8:00 PM (W3)	8:00 AM (W1) 7:00 PM (W2) 10:00 PM (W3)	20%
Television	Regular	60	1	180	30	20%	1	7:00 PM	12:00 AM	15%
Set Top Box	Regular	10	1	180	30	20%	1	7:00 PM	12:00 AM	15%
Washing Machine	Occasional	600	2	30	30	20%	2	6:00 AM (W1) 6:00 PM (W2)	8:00 AM (W1) 8:00 PM (W2)	15%
Vacuum Cleaner	Occasional	1000	1	30	15	20%	1	6:00 AM	8:45 AM	15%
Laptop	Regular	50	1	90	30	15%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 10:00 PM (W2)	10%
Microwave Oven	Occasional	1200	1	60	15	20%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 10:00 PM (W2)	15%
Mixer Grinder	Occasional	500	1	60	15	15%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 10:00 PM (W2)	30%
Water Purifier	Regular	60	1	60	30	15%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 10:00 PM (W2)	30%
Iron	Occasional	1200	1	30	15	15%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 8:00 PM (W2)	30%
Water Pump	Occasional	500	2	30	15	15%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 11:00 PM (W2)	30%
Bathroom Geyser	Regular	2000 (Power Cycle)	1	60	15	10%	2	6:00 AM (W1) 6:00 PM (W2)	8:45 AM (W1) 7:00 PM (W2)	10%
Phone Charger	Regular	5	2	90	15	30%	2	6:00 AM (W1) 6:00 PM (W2)	8:00 AM (W1) 12:00 PM (W2)	35%
Mosquito Repellent	Regular	7	2	480	30	15%	2	6:00 PM (W1) 12:00 AM (W2)	12:00 AM (W1) 6:00 AM (W2)	35%
Music System	Occasional	200	1	60	15	25%	1	7:00 PM	10:00 PM	30%

Table 5.5 Category wise Details of Households

Household Category	Number of households	Distribution Across Building Types							Plinth (Base) Area Span (m ²)		
		One Storey House (Type-I)	Two Storey House (Type-II)	Two Storey Apartment (Type-III)	Three Storey Apartment (Type-IV)	Four Storeyed Apartment (Type-V)	Five Storeyed Apartment (Type-VI)	Six Storeyed Apartment (Type-VII)	Minimum	Maximum	Average
Category 1 Sub Category 1	38 households	0	0	4	3	4	19	8	17.37	41.038	29.944
Category 1 Sub Category 2	17 households	0	0	4	2	4	3	4	16.98	38.532	28.329
Category 1 Sub Category 3	14 households	0	0	3	3	3	3	2	23.668	47.607	39.001
Category 1 Overall	69 households	0	0	11	8	11	25	14	16.98	47.607	31.384
Category 2 Sub Category 1	27 households	2	0	4	7	6	6	2	41.448	64.538	52.66
Category 2 Sub Category 2	12 households	1	0	3	2	3	2	1	43.306	56.292	48.67
Category 2 Sub Category 3	46 households	2	0	7	6	9	15	7	43.306	64.538	55.29
Category 2 Overall	85 households	5	0	14	15	18	23	10	41.448	64.538	53.52
Category 3 Sub Category 1	12 households	2	0	1	3	2	2	2	59.42	92.751	72.197
Category 3 Sub Category 2	6 households	0	0	0	1	1	2	2	66.835	75.13	72.365
Category 3 Sub Category 3	43 households	7	0	2	5	8	12	9	65.86	84.066	71.558
Category 3 Overall	61 households	9	0	3	9	11	16	13	59.42	92.751	71.763
Category 4 Sub Category 1	8 households	5	0	0	0	0	1	2	79.747	110.356	95.685
Category 4 Sub Category 2	0 households	-	-	-	-	-	-	-	-	-	-
Category 4 Sub Category 3	15 households	4	0	2	3	2	2	2	91.638	132.047	100.433
Category 4 Overall	23 households	9	0	2	3	2	3	4	79.747	132.047	98.78
Category 5 Sub Category 1	4 households	4	0	0	0	0	0	0	116.186	129.192	122.689
Category 5 Sub Category 2	0 households	-	-	-	-	-	-	-	-	-	-
Category 5 Sub Category 3	9 households	6	0	2	1	0	0	0	116.186	142.59	125.313
Category 5 Overall	13 households	10	0	2	1	0	0	0	116.186	142.59	124.506
Category 6 Sub Category 1	0 households	-	-	-	-	-	-	-	-	-	-
Category 6 Sub Category 2	0 households	-	-	-	-	-	-	-	-	-	-
Category 6 Sub Category 3	10 households	8	2	0	0	0	0	0	113.422	163.676	147.833
Category 6 Overall	10 households	8	2	0	0	0	0	0	113.422	163.676	147.833
Category 7 Sub Category 1	0 households	-	-	-	-	-	-	-	-	-	-
Category 7 Sub Category 2	0 households	-	-	-	-	-	-	-	-	-	-
Category 7 Sub Category 3	4 households	2	2	0	0	0	0	0	105.742	176.402	145.188
Category 7 Overall	4 households	2	2	0	0	0	0	0	105.742	176.402	145.188
Category 8 Sub Category 1	0 households	-	-	-	-	-	-	-	-	-	-
Category 8 Sub Category 2	0 households	-	-	-	-	-	-	-	-	-	-
Category 8 Sub Category 3	4 households	2	2	0	0	0	0	0	123.12	202.052	148.67
Category 8 Overall	4 households	2	2	0	0	0	0	0	123.12	202.052	148.67
Sub Category 1 Overall	89 households	12	0	10	13	12	28	14	17.37	129.192	52.611
Sub Category 2 Overall	35 households	1	0	7	5	8	7	7	16.98	75.13	42.852
Sub Category 3 Overall	145 households	29	4	16	18	22	33	23	23.668	202.052	79.364
Category Overall	269 households	45	6	32	36	42	67	44	16.98	202.052	65.76

5.2.5 Resource Assessment

The average daily solar radiation, clearness index and average daily temperature for the entire year was 4.74 kWh/m²/day, 0.544 and 12.94 °C respectively (**Figure 3.4** and **Figure 3.5**, Chapter 3).

5.2.6 System Component and Economic Modelling

The system component modelling of various system components was done using Eq. 2.1-Eq. 2.2 for solar panels, Eq. 2.11 – Eq.2.17 for batteries and Eq. 2.18-Eq. 2.20 for converter while economic modelling has been done using Eq.2.21- Eq. 2.24. The economic and technical specifications of the various system components were obtained from local Indian vendors via various online databases and quotation calls (Table 5.6).

Table 5.6 Technical and Financial Details of Off-grid PV system

Component/ Issues	Parameter	Value
PV System (50,190,212,214)	Rated Capacity of each PV module(E_{RPV})	335 W, 100 W
	The cell temperature under standard test conditions($T_{c,STC}$)	25°C
	The incident radiation at standard test conditions($\bar{I}_{T,STC}$)	1kW/m ²
	Ambient Cell Temperature ($T_{a,NOCT}$)	20 °C
	Solar radiation at which the nominal cell operating temperature is defined ($\bar{I}_{T,NOCT}$)	0.8 kW/m ²
	Product of solar transmittance and absorptance($\alpha\tau$)	0.9
	Derating Factor(g_{PV})	88 %
	Nominal Operating Cell Temperature($T_{c,NOCT}$)	44°C
	Temperature Co-efficient(β_p)	-0.41 %/°C
	Efficiency at Standard Conditions(η_c)	17.01 %
	Lifetime	25 Years
	Capital Cost of PV panel	\$312.05/kW (335 W), \$472.05/kW (100 W)
	Replacement Cost of Panel	\$312.05/kW (335 W), \$472.05/kW (100 W)
	Solar Mounting Structure Price (Ground/Rooftop)	\$ 45.51/kW
	Solar Distribution Box prices	\$ 3.88/kW
	Miscellaneous Costs (Wiring, Transportation, Taxes)	\$ 97.6/kW
	Total Capital Costs of the PV system	\$459.01/kW (335W), \$619.01(100 W)
	Operation and Maintenance Cost	\$25/year
	Total Installation Area Coverage per Module (330 W)	1.734 m ²
	Battery (50,198,212,213)	Panel inclination
Tracking System		Maximum Power Point Tracking
Battery Type		Lead Acid
Nominal Voltage		12 V
Nominal Capacity		150 Ah
Round Trip Efficiency		85 %
Minimum Battery Life		4 years
Minimum State of Charge		20%
Capital Cost		\$157.14/ battery
Operation and Maintenance Cost		\$ 10/year
Converter (50,198,212,213)	Replacement Cost	\$117.75/battery
	Battery throughput	2304 kWh @ 80% Depth of Discharge
	Converter Rated Capacity	600 Watts, 1.5 kW, 100 watts
	Inverter Efficiency	98.3%
	Lifetime	25 years
	Capital Cost	\$140/kW
	Operation and Maintenance Cost	\$10/year
	Replacement Cost	\$140/kW
Constraints (50,198,212,213)	Safety Factor/ Inverter Efficiency	1.10
	Interest Rate	8%
	Inflation Rate	3.5%
	Annual Capacity Shortage	0 %
	Project lifetime	25 years

For determining the feasibility of the system in terms of roof area available, the investigation assumed that every household or house in the building is likely to adapt an autonomous rooftop PV nanogrid or microgrid and the rooftop area or plinth area in any building is divided as per the apartment/ house plinth area (**Figure 5.4**) in a particular floor which is further equally divided among the households along the “vertical line of the building” (237). Hence, to determine the space feasibility, the following parameter has been formulated based on the techniques used in (233,234):

$$F_{fl,num} = \frac{A_{roof}^{eff}}{A_{PV,system}} \quad (5.1)$$

Where $F_{fl,num}$ is the Floor Number (FN), $A_{PV,system}$ is the panel area requirement for the PV system, A_{roof}^{eff} is the effective roof area available for a “vertical line” of a building.

The effective roof area per house is given by (233,234):

$$A_{roof}^{eff} = \frac{A_{base}}{\cos \beta_{roof}} U_r \quad (5.2)$$

Where

$$U_r = U_{ori}U_{so}U_{abs} \quad (5.3)$$

Where “ A_{base} is base or plinth area of the house or apartment, β^{roof} is the slope angle of the roof, U_r is the overall roof area utilization factor, U_{ori} is utilization factor of orientation, U_{so} is the shadows and obstacle factor including inter-row shadings between PV panels, U_{abs} is the absolute reduction factor due to cultural, religious and design issues, height of the building”. The value of U_r is assumed to be 0.70 (234–236). The slope angle for pitched roofs ranges between 20^0 - 30^0 while for flat roofs it is 0^0 (233). In this investigation, the PV panels are assumed to lie flat on the pitched roofs which are assumed to be inclined at 27.5^0 , but lie inclined at 27.5^0 on flat roofs. This makes the panels inclined at 27.5^0 (Table 5.6) with the horizontal for both the roof types. Thus, the slope angle (β^{roof}) for both pitched roof and flat roofs is considered as 0^0 . Only the panel area has been considered in equation (1) as the converters are assumed to be wall mounted on roof walls or building walls and the batteries are assumed to be stacked in basements, rooms or in the balconies inside the buildings. The possible conditions obtained via equation (1) for the location are presented in **Table 5.7**. After deducing the condition of space feasibility for a particular Category based on FN from **Table 5.7**, the Percentage Feasibility for a particular Category can be defined by the following equation:

$$\text{Percentage Feasibility} = \frac{N_f}{N_t} \times 100 \quad (5.4)$$

N_t is the total number of houses in a particular Category, N_f is the total number of houses in a particular Category that satisfy the condition of space feasibility for that Category (**Table 5.7**).

Table 5.7 Possible conditions for space feasibility

Conditions	Type of Building in which the PV system will be feasible in terms of space
$F_{fl,num} < 1$	No Type
$1 \leq F_{fl,num} < 2$	Type I and II
$2 \leq F_{fl,num} < 3$	Type I, II and III
$3 \leq F_{fl,num} < 4$	Type I, II, III and IV
$4 \leq F_{fl,num} < 5$	Type I, II, III, IV and V
$5 \leq F_{fl,num} < 6$	Type I, II, III, IV, V and VI
$6 \leq F_{fl,num}$	All types

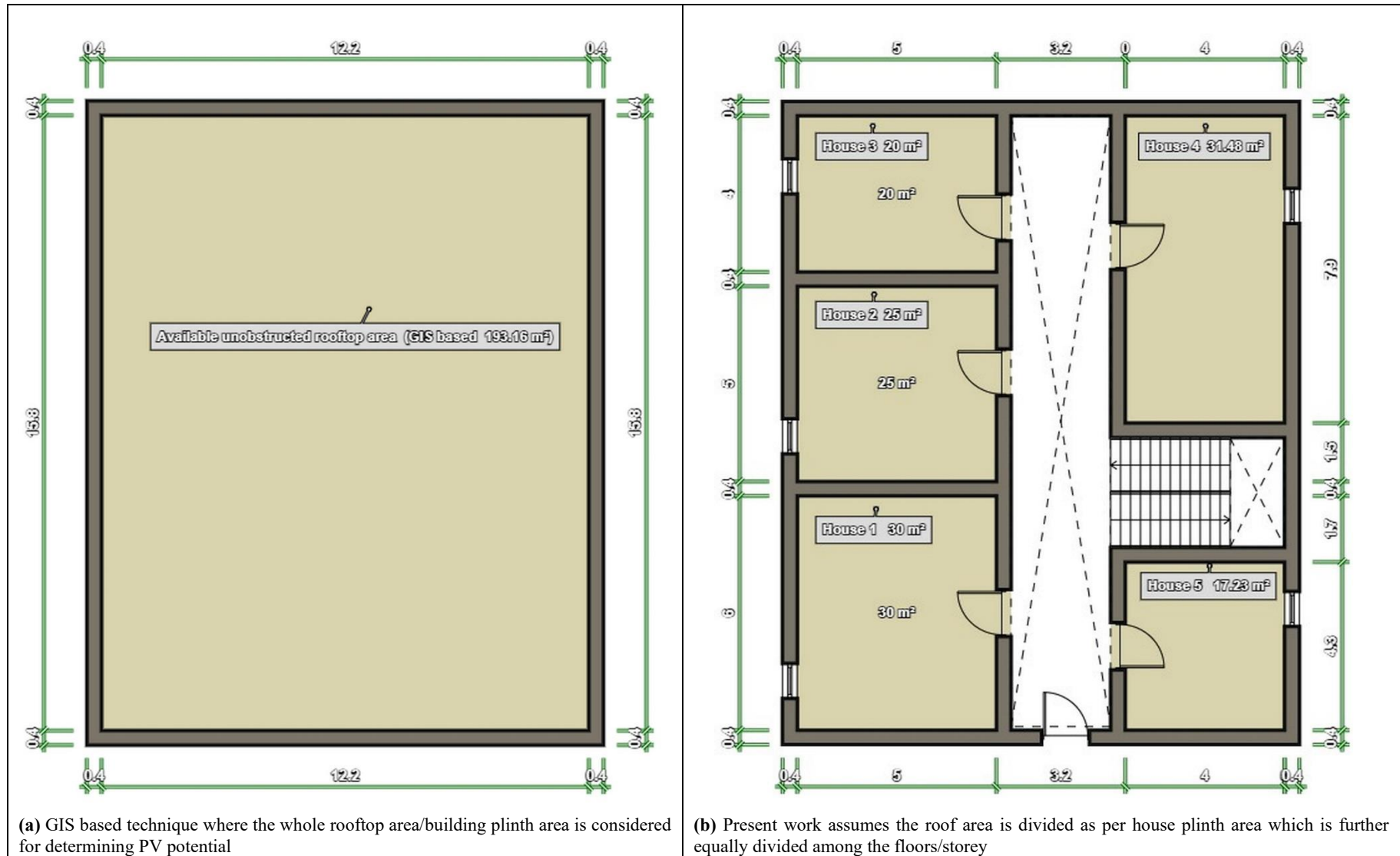


Figure 5.4 Rooftop area availability per household compared to overall rooftop area availability (GIS) for PV panel installation

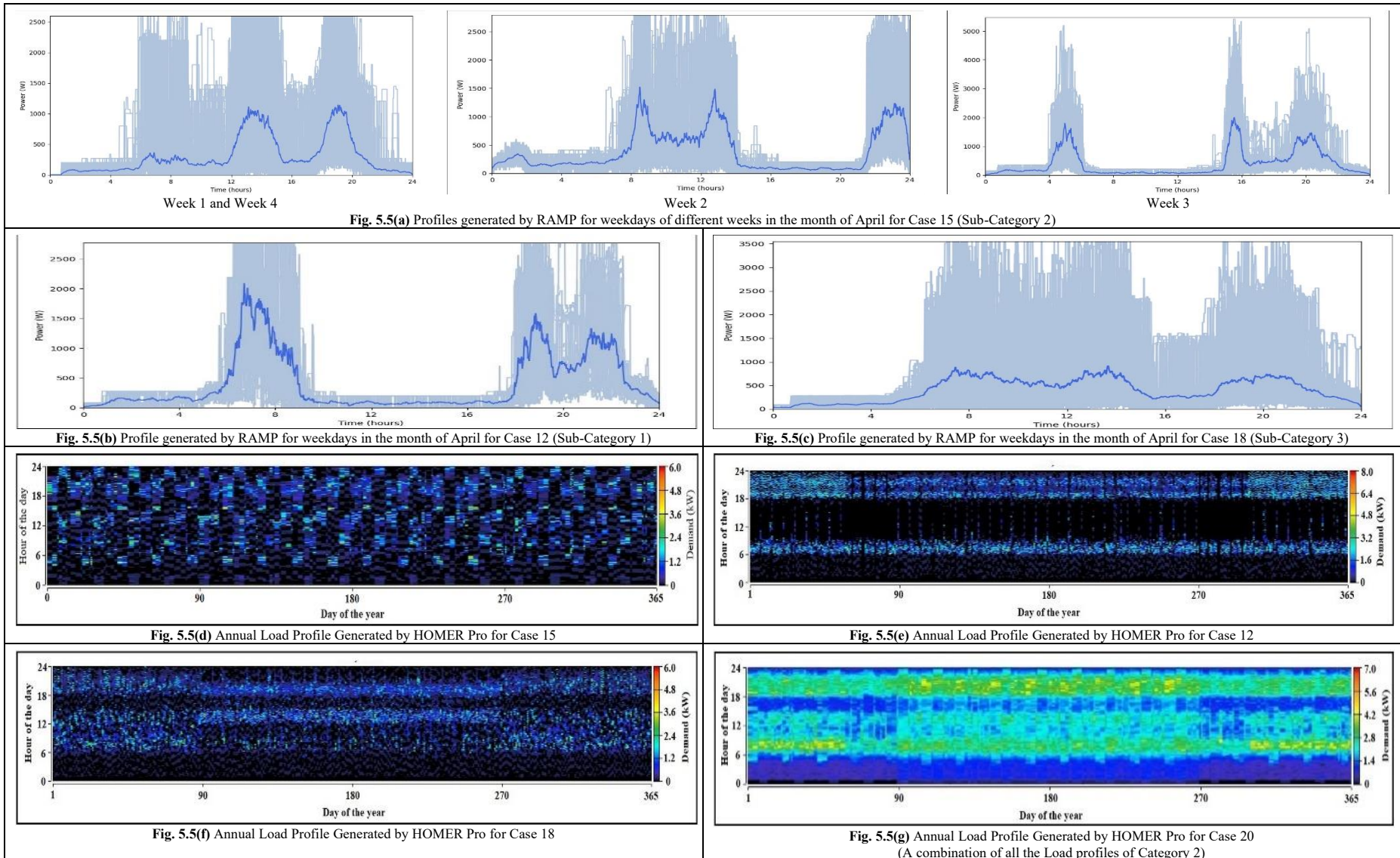


Figure 5.5 Sample Load profiles Generated by RAMP and HOMER PRO for different Sub-Categories showing the variations in user behavior.

5.3 Results

5.3.1 Simulation Results of HOMER PRO

The salient results generated by RAMP and HOMER PRO are provided in **Table 5.8** and the optimum system configurations are presented in **Table 5.9**.

The average monthly load ranged between 14.7 kWh and 674.1 kWh, peak load ranged between 0.09 kW and 17.34 kW and load factor ranged between 0.04 and 0.36 (**Table 5.8**). On comparing only Categories, Category 7 (Case 50) had the highest average monthly load of 402.3 kWh while Category 1 (Case 10) had the least at 87.6 kWh. Category 7 also had the highest peak load of 7.34 kW while Category 2 (Case 20) had the least at 0.66 kW. Category 2 had the highest load factor of 0.3 while Category 7 had the least at 0.08. On comparing only Sub-Categories, Sub-Category 3 (Case 56) had the highest monthly average of 233.1 kWh while Sub-Category 1 (Case 54) had the least of 110.1 kWh. Sub-Category 2 (Case 55) had the highest peak load of 1.03 kW while Sub-Category 1 had the least at 0.82. The average monthly load, average peak load and average load factor for all the surveyed households (Case 57) was 181.2 kWh, 0.8 kW and 0.31 respectively. Significant differences in load demand variations on a day-to-day and time step basis were also observed among the Cases.

The LCOE ranged between 0.160 \$/kWh and 0.405 \$/kWh and the panel area ranged between 3.44 m² and 86.06 m². On comparing Categories, Category 1 had the highest LCOE at 0.197 \$/kWh while Category 5 (Case 44) had the least at 0.160 \$/kWh. Category 8 (Case 53) had the highest panel area requirement of 49.91 m² while Category 1 had the least of 12.05 m². On comparing Sub-Categories, Sub-Category 2 had the highest LCOE at 0.207 \$/kWh and Sub-Category 3 had the least at 0.160 \$/kWh. Sub-Category 1 and Sub-Category 2 both had the least panel area of 13.77 m² while Sub-Category 3 had the highest of 27.54 m². The average LCOE of all the households (Case 57) was 0.164 \$/kWh and the panel area requirement was 24.10 m².

5.3.2 Correlation Analysis

To comprehend the impact of various parameters on LCOE and panel area, correlation analysis was conducted using Pearson's correlation co-efficient (226) and Spearman Rank correlation Co-efficient (238). Strongly and positive correlations were observed for number of dwelling rooms with average category load ($r=0.93$, $p<0.001$), peak category loads ($r=0.8$, $p<0.001$) and average category plinth area/house ($r=0.978$, $p<0.001$) respectively; and also for panel area with average load ($r=0.977$, $p<0.001$), peak load ($r=0.857$, $p<0.001$), average category plinth area/house ($r=0.992$, $p<0.001$) and number of dwelling rooms ($r=0.98$, $p<0.001$) respectively. Thus, the panel area increased with the increase in number of dwelling rooms or plinth area/ house due to increase in the average load or peak load of the household. The correlations for load factor with the number of dwelling rooms and panel area were insignificant and very weak ($r=0.22$, $p<0.01$) respectively to draw any conclusion.

For LCOE, no significant correlations were observed with average load demand, peak load, number of dwelling rooms or load factor. However, the LCOE correlated strongly and positively with percentage random day-to-day variations ($r=0.817$, $p<0.001$, $n=57$) and percentage random time step variations of load demand ($r=0.753$, $p<0.001$, $n=57$). The LCOE correlated moderately and negatively with the number of houses considered to determine the average load for each case ($r=-0.637$, $p<0.001$, $n=57$). The percentage random day-to-day variations ($r=-0.857$, $p<0.001$, $n=57$) and percentage timestep variations of load demand ($r=-0.817$, $p<0.001$, $n=57$) showed strong negative correlations with the number of houses considered to determine the average load for each case. Thus, system LCOE for single houses were higher compared to system LCOE for multiple/grouped houses due to higher percentage variations in load demand for single houses. In fact, for monthly loads below 50 kW for a single house (Cases 1, 4, 11 and 14), the LCOEs were exceptionally high, along with the highest percentage day-to-day and time step load variations. Hence, sharing of nanogrids between multiple users generally reduce the day-to-day and time step load variations thus smoothening the load profiles which eventually reduce the LCOE compared to individual users. However, the type of user classified by the sub-categories in this investigation also has a critical role in determining the LCOE.

5.3.3 Rooftop Space Feasibility

The details of the percentage feasibility and Floor number (FN) for each Category are presented in **Figure 5.6**. The FN ranged between 1.82 and 2.36 with the least being observed for Category 1 while the highest being observed for Category 5. Thus, off-grid PV nanogrid system will be at least feasible for 1-storey building for Categories 1 and 2 and can be comfortably feasible for 2-storey buildings for the remaining Categories.

The percentage feasibility was the least for Category 1 (0%) and highest for Category 6, 7 and 8 (100%). The feasibility for Category 1 was 0% despite having FN greater than 1 as there were no houses of Category 1 (One Room) in 1-storey building among the surveyed households (**Table 5.5**). The feasibility increased to 100 % for Category 6, 7 and 8 as the houses under these Categories belonged to 1-storey and 2-storey buildings (**Table 5.5**).

Table 5.8 Simulation results generated by HOMER PRO

Case Number	Case Details	Average Monthly Load (kWh)	Peak Load (kW)	Load Factor	Day-to-Day Variation (%)	Time Step Variation (%)	LCOE (\$/kWh)	Panel Area Requirement (m ²)
Case 1	Category 1- Sub Category 1-Criteria 1	14.7	0.09	0.23	32.79	1183	0.387	3.44
Case 2	Category 1- Sub Category 1-Criteria 2	251.7	7.04	0.05	20.68	115.48	0.232	30.98
Case 3	Category 1- Sub Category 1-Criteria 3	71.7	1.16	0.09	16.48	65.76	0.215	10.33
Case 4	Category 1- Sub Category 2-Criteria 1	17.1	0.18	0.13	38.52	204.36	0.405	5.16
Case 5	Category 1- Sub Category 2-Criteria 2	209.4	4.6	0.06	23.204	125.713	0.206	20.88
Case 6	Category 1- Sub Category 2-Criteria 3	87.3	1.13	0.11	7.87	79.86	0.203	12.05
Case 7	Category 1- Sub Category 3-Criteria 1	56.7	0.22	0.36	17.78	69.29	0.225	29.26
Case 8	Category 1- Sub Category 3-Criteria 2	277.8	6.58	0.06	25.86	108.45	0.192	24.10
Case 9	Category 1- Sub Category 3-Criteria 3	143.1	1.06	0.19	4.97	25.39	0.187	22.36
Case 10	Category 1- Average	87.6	0.78	0.15	11.79	36.220	0.197	12.05
Case 11	Category 2- Sub Category 1-Criteria 1	16.8	0.14	0.17	33.12	623.872	0.351	3.44
Case 12	Category 2- Sub Category 1-Criteria 2	289.2	7.37	0.05	22.95	201.15	0.226	32.68
Case 13	Category 2- Sub Category 1-Criteria 3	115.8	1.0	0.16	5.78	44.95	0.202	17.20
Case 14	Category 2- Sub Category 2-Criteria 1	36.9	1.13	0.05	41.253	344.53	0.319	6.88
Case 15	Category 2- Sub Category 2-Criteria 2	242.7	5.54	0.06	19.049	133.270	0.221	37.86
Case 16	Category 2- Sub Category 2-Criteria 3	122.1	1.69	0.1	15.047	76.32	0.224	15.49
Case 17	Category 2- Sub Category 3-Criteria 1	89.7	1.31	0.09	8.83	106.11	0.174	10.33
Case 18	Category 2- Sub Category 3-Criteria 2	243.6	5.85	0.06	20.52	122.583	0.20	25.82
Case 19	Category 2- Sub Category 3-Criteria 3	166.2	0.97	0.24	2.7	17.36	0.170	22.37
Case 20	Category 2-Average	144.6	0.66	0.30	3.64	19.76	0.175	18.93
Case 21	Category 3- Sub Category 1-Criteria 1	97.8	2.32	0.06	13.17	110.625	0.224	13.77
Case 22	Category 3- Sub Category 1-Criteria 2	411	8.06	0.07	12.5	110.429	0.208	37.84
Case 23	Category 3- Sub Category 1-Criteria 3	174.3	2.35	0.1	9.59	51.34	0.196	20.65
Case 24	Category 3- Sub Category 2-Criteria 1	97.2	1.97	0.07	16.495	96.529	0.203	12.04
Case 25	Category 3- Sub Category 2-Criteria 2	316.2	10.45	0.04	18.326	147.737	0.268	48.19
Case 26	Category 3- Sub Category 2-Criteria 3	159	2.13	0.10	8.82	79.98	0.208	25.8
Case 27	Category 3- Sub Category 3-Criteria 1	94.5	2.79	0.06	16.76	92.37	0.233	13.77
Case 28	Category 3- Sub Category 3-Criteria 2	363	7.38	0.07	20.31	106.386	0.192	43.03
Case 29	Category 3- Sub Category 3-Criteria 3	197.1	1.04	0.26	2.75	17.654	0.166	25.82
Case 30	Category 3-Average	189	0.9	0.29	2.788	18.126	0.167	22.37
Case 31	Category 4- Sub Category 1-Criteria 1	93.3	2.52	0.05	19.69	108.75	0.238	12.05
Case 32	Category 4- Sub Category 1-Criteria 2	392.1	9.05	0.06	15.07	116.48	0.226	46.44
Case 33	Category 4- Sub Category 1-Criteria 3	214.5	2.9	0.1	7.91	48.7	0.204	25.82
Case 34	Category 4- Sub Category 3-Criteria 1	149.1	2.97	0.07	18.118	107.544	0.277	17.21
Case 35	Category 4- Sub Category 3-Criteria 2	622.2	14.26	0.06	18.06	99.71	0.189	68.84
Case 36	Category 4- Sub Category 3-Criteria 3	323.4	2.07	0.22	4.57	27.397	0.157	39.56
Case 37	Category 4-Average	285.3	1.9	0.21	3.94	23.88	0.165	30.96
Case 38	Category 5- Sub Category 1-Criteria 1	107.4	2.33	0.06	18.553	111.764	0.219	13.77
Case 39	Category 5- Sub Category 1-Criteria 2	396.3	9.51	0.06	15.38	116.61	0.237	41.28
Case 40	Category 5- Sub Category 1-Criteria 3	227.7	3.74	0.08	10.02	68.98	0.206	20.65
Case 41	Category 5- Sub Category 3-Criteria 1	188.4	4	0.07	15.897	105.544	0.216	27.54
Case 42	Category 5- Sub Category 3-Criteria 2	674.1	17.34	0.05	17.664	101.924	0.220	86.06
Case 43	Category 5- Sub Category 3-Criteria 3	455.1	4.4	0.14	7.75	36.6	0.160	48.19
Case 44	Category 5-Average	385.5	3.48	0.15	5.427	32.445	0.160	39.59
Case 45	Category 6- Sub Category 3-Criteria 1	225.6	6.22	0.05	14.88	99.95	0.208	29.26
Case 46	Category 6- Sub Category 3-Criteria 2	560.7	17.22	0.05	19.31	120.719	0.209	56.80
Case 47	Category 6-Average	351.3	3.42	0.14	6.308	38.31	0.170	46.47
Case 48	Category 7- Sub Category 3-Criteria 1	238.5	5.2	0.06	14.84	101.329	0.200	30.96
Case 49	Category 7- Sub Category 3-Criteria 2	492	15.31	0.04	22.645	129.404	0.217	53.35
Case 50	Category 7-Average	402.3	7.34	0.08	10.605	65.088	0.174	44.75
Case 51	Category 8- Sub Category 3-Criteria 1	232.5	5.21	0.06	16.24	96.94	0.206	30.96
Case 52	Category 8- Sub Category 3-Criteria 2	603.6	16.96	0.05	21.74	129.617	0.207	68.8
Case 53	Category 8-Average	378.3	5.08	0.1	10.14	66.88	0.177	49.91
Case 54	Sub-Category 1-Average	110.1	0.81	0.19	2.609	38.27	0.199	13.77
Case 55	Sub-Category 2-Average	113.1	1.03	0.15	11.16	67.498	0.207	13.77
Case 56	Sub-Category 3-Average	233.1	0.98	0.33	1.89	10.664	0.160	27.54
Case 57	All Category -Average	181.2	0.8	0.31	4.427	12.750	0.164	24.10

Hence, despite having small variations in FN for different Categories, the percentage space feasibility of PV nanogrid systems was higher for households with larger number of dwelling rooms (Categories 6-8) as these houses existed in the form of private single or double-storey low-rise buildings where the roof area was entirely available for that particular household unlike in multi-storied buildings where the roof area was shared among the households across floors. For the average load of all the Categories (Case 57), the FN was 1.91 implying that only households in one-storied buildings, that is 45 households or 16.72% of the total surveyed households (**Table 5.5**) shall be able to viably install a fully autonomous microgrid for such a load profile and magnitude.

The variations in FN were not significant as the panel area requirement increased almost linearly with the rooftop area or the apartment plinth area (Sec 5.3.2). Thus, a large house plinth area or rooftop area need not be an advantage for PV nanogrids if the electrical demand is high and uncoordinated as observed in this case study.

5.3.4 Subsidy for Competitiveness with grid

The LCOE in this work was higher than the existing grid prices of 0.105 \$/kWh in Sikkim [206]. On conducting a sensitivity analysis on Case 57, a minimum subsidy of 50 percent on the capital cost of the entire system including PV panels, batteries and converter system reduced the LCOE to 0.104 \$/kWh which made the system quite competitive with the grid.

Table 5.9 Optimum System Configuration Details for each Case obtained by HOMER PRO

Category Details	Configuration in Terms of Power Output			Peak Month	NPC (\$)	Configuration in terms of quantity		
	PV (kW)	Batteries (kW)	Converter (kW)			PV Panels (335 watts)	Battery (1.8 kWh)	Converter (Rated Power in kW)
Case 1	0.670	3.6	0.1	June	1040	2	2	1(0.1)
Case 2	6.03	21.6	8.1	December	10689	18	12	5 (1.5), 1(0.6)
Case 3	2.01	5.4	1.3	January	2840	6	3	2 (0.6), 1(0.1)
Case 4	1.005	3.6	0.2	April	1264	3	2	2 (0.1)
Case 5	4.02	19.8	5.1	August	7893	12	11	3 (1.5), 1 (0.6)
Case 6	2.345	7.2	1.3	August	3250	7	4	2 (0.6), 1 (0.1)
Case 7	2.01	5.4	0.3	June	2340	6	3	3 (0.1)
Case 8	4.69	23.4	7.5	January	9767	14	13	5 (1.5)
Case 9	4.355	9	1.2	May	4906	13	5	2 (0.6)
Case 10	2.345	7.2	0.9	May	3165	7	4	1 (0.6), 3 (0.1)
Case 11	0.670	3.6	0.2	August	1085	2	2	2 (0.1)
Case 12	6.365	27	8.1	December	11986	19	15	5 (1.5), 1(0.6)
Case 13	3.35	9	1.2	May	4298	10	5	2 (0.6)
Case 14	1.34	5.4	1.3	September	2150	4	3	2 (0.6), 1(0.1)
Case 15	7.37	16.2	6.1	April	9840	22	9	4 (1.5), 1(0.1)
Case 16	3.015	14.4	1.9	April	5002	9	8	3 (0.6), 1(0.1)
Case 17	2.010	5.4	1.5	November	2854	6	3	1 (1.5)
Case 18	5.025	19.8	6.6	February	8906	15	11	4 (1.5), 1(0.6)
Case 19	4.355	10.8	1.2	May	5165	13	6	2 (0.6)
Case 20	3.685	10.8	0.8	June	4622	11	6	1 (0.6), 2 (0.1)
Case 21	2.68	7.2	2.6	February	4009	8	4	4 (0.6), 2 (0.1)
Case 22	7.37	41.4	9	January	15660	22	23	6 (1.5)
Case 23	4.02	14.4	2.6	February	6258	12	8	4 (0.6), 2(0.1)
Case 24	2.345	7.2	2.1	June	3544	7	4	1 (1.5), 1 (0.6)
Case 25	9.715	30.6	12	November	15512	28	17	8 (1.5)
Case 26	5.025	10.8	2.4	July	6050	15	6	4 (0.6)
Case 27	2.68	7.2	3.1	February	4029	8	4	2 (1.5), 1(0.1)
Case 28	8.375	25.2	8.1	December	12782	25	14	5 (1.5), 1 (0.6)
Case 29	5.025	12.6	1.2	September	5974	15	7	2 (0.6)
Case 30	4.355	14.4	1	May	5790	13	8	1 (0.6), 4 (0.1)
Case 31	2.345	9	2.8	May	4062	7	5	1 (1.5), 2 (0.6), 1(0.1)
Case 32	9.045	37.8	10.2	July	16244	27	21	6 (1.5), 2 (0.6)
Case 33	5.025	19.8	3.3	May	7992	15	11	2 (1.5), 3(0.1)
Case 34	3.35	10.8	3.3	July	7559	10	6	2 (1.5), 3(0.1)
Case 35	13.4	61.2	16.2	November	5169	40	34	10 (1.5), 2(0.6)
Case 36	7.705	18	2.4	November	9293	23	10	4(0.6)
Case 37	6.03	18.0	2.2	December	8637	18	12	1(1.5), 1 (0.6), 1(0.1)
Case 38	2.68	9	2.6	April	4304	8	5	4 (0.6), 2(0.1)
Case 39	8.04	48.6	10.5	September	17185	23	28	7 (1.5)
Case 40	4.02	25.2	4.2	September	8600	12	14	2 (1.5), 2 (0.6)
Case 41	5.36	14.4	4.5	August	7451	16	8	3 (1.5)
Case 42	16.75	55.8	19.2	December	27152	50	31	12 (1.5), 2 (0.6)
Case 43	9.38	30.6	5.1	February	13361	28	17	3 (1.5), 1(0.6)
Case 44	7.705	27.0	3.9	February	11299	23	15	4 (0.6)
Case 45	5.695	14.4	7.2	July	8578	17	8	4 (1.5), 2 (0.6)
Case 46	11.055	24	19.2	December	21480	33	15	12 (1.5), 2 (0.6)
Case 47	9.045	19.8	3.8	November	10954	27	11	2 (1.5), 1 (0.6), 2(0.1)
Case 48	6.03	16.2	6	August	8728	18	9	4 (1.5)
Case 49	10.385	39.6	17.1	January	19576	31	22	11 (1.5), 1(0.6)
Case 50	8.71	23.4	8.1	January	12828	26	13	5 (1.5), 1 (0.6)
Case 51	6.03	16.2	6	September	8763	18	9	4 (1.5)
Case 52	13.4	45	18.6	November	22689	40	25	12 (1.5), 1 (0.6)
Case 53	9.715	21.6	6	February	12281	29	12	4 (1.5)
Case 54	2.680	10.8	0.9	June	4024	8	6	1 (0.6), 3 (0.1)
Case 55	2.680	12.6	1.2	April	4283	8	7	2 (0.6)
Case 56	5.36	16.2	1.2	November	6829	16	9	2 (0.6)
Case 57	4.69	10.8	0.9	July	5429	14	6	1 (0.6), 3 (0.1)

5.3.5 Sensitivity Analysis

To realize a broader perspective of this investigation especially in India, sensitivity analysis was conducted for Case 57, which is a good sample representation of the load profile/household for this investigation and can be considered as a generic load profile for urban localities in different parts of India. Several critical and uncertain criteria namely depth of discharge (DOD) of batteries, battery life, battery throughput, daily solar radiation, daily ambient temperature, average urban plinth area per household, effective roof utilization factor (U_r) and monthly load demand per household were chosen as sensitivity variables by taking into consideration the urban data from all the states and union territories of India.

5.3.5.1 Impact of battery life and DOD on system configuration

To perform this sensitivity analysis, the battery capacity was allowed to change while keeping panel capacity constant at 4.69 kWh.

With reduction in DOD, the number of cycles to failure increased resulting in a longer life of the battery (195,197) (**Figure 5.7(a)**). However, the battery throughput did not change significantly with increase in battery life or reduction in DOD. The number of the batteries or total battery capacity increased with decrease in DOD or increase in minimum state of charge (SOC) thus increasing the capital costs of batteries and the system LCOE.

However, at a constant DOD (20%), the LCOE decreased with increase in number of battery cycles due to increase in battery throughput (**Figure 5.7(b)**). Thus, batteries having longer life at higher DOD reduces the system LCOE due to increase in battery throughput and consequent reduction in system battery capacity.

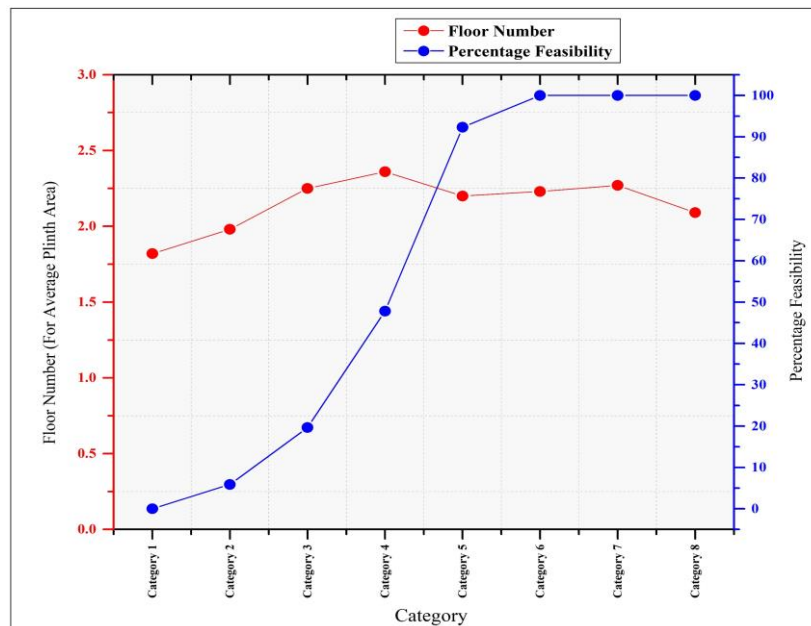


Figure 5.6 Rooftop Space Feasibility Investigation for Various Categories

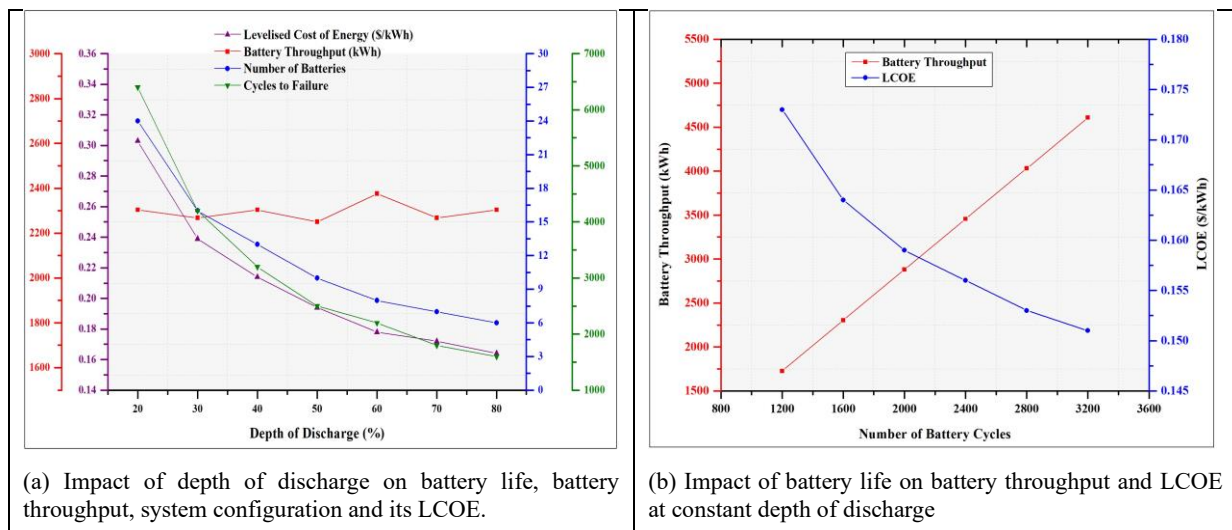


Figure 5.7 Impact of battery parameters on system configuration and LCOE

5.3.5.2 Impact of Annual Solar Radiation and Ambient Temperature on LCOE and system capacity

Figure 5.8(a) and **Figure 5.8(e)** represent the average annual global solar radiation and average annual temperature ranges for India (240,241). The LCOE decreased with increase in average annual solar radiation and increased with increase in average annual temperature. At a particular average annual temperature, decrease in LCOE ranged from 19.89 % to 22.16 % as the average annual radiation increased from 3.25 kWh/m²/day to 5.75 kWh/m²/day with the least variation being observed at the highest temperature (30⁰ C/day) and the highest variation being observed at the lowest temperature (12.94⁰C/day). Thus, in colder places, radiation variations will have more impact on LCOE than hotter places. At a particular average annual radiation, increase in LCOE ranged from 3.09 % to 4.63 % as the average annual temperature increased from 12.94 °C/day to 30⁰C/day with the least variation being observed at the lowest radiation (3.25 kWh/m²/day) and the highest variation being observed at the highest radiation (5.75 kWh/m²/day). Thus, the impact of radiation on LCOE was higher compared to temperature in India.

The impact of average solar radiation and temperature on the number of solar panels, batteries and total system capacity (panels plus battery) are presented in **Figure 5.8(b)**, **Figure 5.8(c)** and **Figure 5.8(d)** respectively. No significant trend was observed for the impact of temperature on the either number of PV panels, batteries or system capacity and of solar radiation on number of solar panels. However, a reduction in the number of batteries and overall capacity of the system (PV and batteries) was observed with increase in the average annual solar radiation, at a particular temperature.

The distribution of system LCOE, the average annual global solar radiation ranges (240), the average annual temperature ranges (242) and the corresponding sensitivity variables for radiation and temperature across various states and union territories of India is shown in **Figure 5.8(e)** (Abbreviations at **Table 5.10**). The empty spaces indicate that the absence of any region in that combination of radiation and temperature range. Localities in Arunachal Pradesh (AP) had the highest LCOE (0.195 \$/kWh) while localities in Jammu and Kashmir (JK) and Ladak had the lowest (0.151 \$/kWh).

5.3.5.3 Impact of Average Monthly Load on LCOE, panel area and system capacity

The monthly load demand varied widely across the population of the country and can widely impact the system configuration and overall PV panel area requirement. **Figure 5.9(a)** represents the percentage distribution of households in India in terms of monthly load (242,243). 62 % and 95 % of the households in India have monthly loads below 100 kWh and 300 kWh, respectively.

For the same load profile (Case 57), the LCOE was slightly higher for low monthly loads of 30 kWh (0.178 \$/kWh) and 50 kWh (0.172 \$/kWh) which almost becomes constant at 0.163 \$/kWh for monthly loads beyond 100 kWh (**Figure 5.9(b)**). The higher LCOE at low monthly loads was due to an oversized system including panels (335-watts), batteries and inverter (**Figure 5.9(b)**) due to unavailability of exactly sized components in the market or higher capital costs for smaller components (100-watts panels) (Table 5.6). The overall capacity of the system (panel area and the number of batteries) increased almost linearly with the increase in the monthly load demand (**Figure 5.5(b)**).

5.3.5.4 Impact of Average Monthly Load and Effective Roof Utilization factor on FN

The Floor Number (FN) determines the building type (**Table 5.5**) in storey (number of floors) in which a PV nanogrid system, particularly its panels, would comfortably fit at the rooftop area and provide electricity at full autonomy, if the rooftop area is equally divided among the households/apartments along the “vertical line of the building”. It depends on the apartment plinth area, average monthly load, effective roof utilization factor [U_r] and PV panel area. An FN value lesser than 1 indicates area infeasibility for the nanogrid. To have a broader perspective of the rooftop feasibility of the off-grid PV nanogrid for the generic case (Case 57), a sensitivity analysis was performed with respect to plinth area and the monthly load demand across all the states and union territories of India for different values of U_r . The average plinth area/household across the country in urban localities was deduced by assuming an additional 10% area over the average floor area for various states and union territories (195) (**Table 5.10**). The average plinth area/house for entire India (AI) was 50.754 m² with

the lowest for Dadra and Nagar Haveli (DNH) at 23.815 m² and the highest for Kerala (KE) at 92.18 m².

The sensitivity analysis results are presented in Fig. 5.10 for the three variable input parameters namely U_r , average plinth area/household and monthly load demand. The FN increased with decrease in monthly load demand and with increase in U_r or average plinth area/household (**Figure 5.10(a)-Figure 5.10(f)**). For the highest U_r value of 0.974 (**Figure 5.10(f)**) and least monthly load of 30 kWh/household, the FN ranged between 10.44 for DNH to 40.44 for KE. Thus, with minimal radiation obstructions, proper panel orientation and spacing and almost full rooftop availability for installation, even 10-storey buildings in DNH and 40-storey buildings in KE can adopt off-grid rooftop PV nanogrids if the monthly load demand for such buildings remains below 30 kWh/household. The FN reduced to 3.76 for DNH and 14.75 for KE as the monthly demand increased from 30 kWh/household to 50 kWh/household (**Figure 5.10(f)**). For monthly loads up to 100 kWh/household (**Figure 5.10(a)-Figure 5.10(f)**), the system will be feasible at least up to 1-storey buildings in all the states and union territories of India. For the highest monthly load of 300 kWh/household and highest $U_r=0.974$ (**Figure 5.10(f)**), the FN remained below 2 for all the states and exceeded 1 for only four states (KE, MN, MZ and UK). For U_r of 0.22 (**Figure 5.10(a)**), the FN reduced to 2.36 for DNH and 9.13 for KE for monthly load of 30 kWh/household and went below 1 for monthly loads of 200 kWh/household for all the states and union territories (**Figure 5.10(a)-Figure 5.10(f)**). For U_r between 0.371 and 0.824 (**Figure 5.10(b)-Figure 5.10(e)**), a more realistic scenario in India, the FN remained above 1 for almost all the states and union territories of India for monthly loads of 100 kWh/household. For U_r of 0.6724 and above (**Figure 5.10(d)-Figure 5.10(f)**), the FN remained above 1 for almost all the states and union territories of India for monthly load up to 200 kWh/household.

Table 5.10 Details of Average Plinth Area available across various locations in India

Sl.No.	States and Union Territories	Abbreviation	Average Floor Area per Household	Average Plinth Area per Household
1	Dadra & Nagar Haveli	DNH	21.65	23.815
2	Daman & Diu	DD	23.49	25.839
3	Himachal Pradesh	HP	34.2	37.62
4	A & N Islands	ANI	36.7	40.37
5	West Bengal	WB	36.73	40.403
6	Odisha	OR	37.29	41.019
7	Telangana	TE	38.36	42.196
8	Delhi	ND	40.57	44.627
9	Maharashtra	MA	41.86	46.046
10	Tamil Nadu	TN	42.14	46.354
11	Meghalaya	MG	42.99	47.289
12	Gujarat	GU	43	47.3
13	Arunachal Pradesh	AP	43.82	48.202
14	Jharkhand	JH	44.07	48.477
15	Uttar Pradesh	UP	45.9	50.49
16	All India	AI	46.14	50.754
17	Tripura	TR	48.74	53.614
18	Madhya Pradesh	MP	49.01	53.911
19	Karnataka	KA	49.3	54.23
20	Chhattisgarh	CH	49.43	54.373
21	Bihar	BI	49.89	54.879
22	Chandigarh	CN	49.97	54.967
23	Sikkim	SK	50.28	55.308
24	Rajasthan	RA	50.68	55.748
25	Assam	AS	54.3	59.73
26	Nagaland	NA	55.92	61.512
27	Haryana	HA	56.33	61.963
28	Jammu & Kashmir & Ladakh	JK, LD	59.56	65.516
29	Goa	GO	63.68	70.048
30	Puducherry	PU	64.07	70.477
31	Lakshadweep	LK	64.19	70.609
32	Punjab	PU	65.66	72.226
33	Uttarakhand	UK	70.36	77.396
34	Manipur	MN	70.58	77.638
35	Mizoram	MZ	78.63	86.493
36	Kerala	KE	83.8	92.18

5.4 Limitations of Methodology

The investigation conducted via snowball sampling in this case-study may not be free from biasness. The RAMP software relies on the accuracy of details provided by the interviewees which may deviate simply due to the poor memory of the interviewees if taken for a long duration like a year. HOMER Pro simulations rely more on energy balance than on exact voltage-current relations and does

not directly consider possibilities like impacts of power generation losses, transmission losses, equipment failure. Due to these limitations, this investigation provides an approximate outcome which may require a more detailed investigation prior to installation in a house-to-house basis.

5.5 Discussion

Several places in Sikkim have transformed from villages to suburbs during the last decade including the Rangpo wards. Thus, while performing sensitivity analysis for plinth area, the average plinth area of Sikkim (overall) was considered for Sikkim (urban) to realize this change. In this case study, the average plinth area/household was higher than that of Sikkim (overall). This may be the result of a sampling bias or may be due to an increase in average plinth area/household over the past decade due to improvement in the economic status of people in Sikkim.

In this study, the average monthly load/household increased with the number of dwelling rooms and floor area like in previous researches (221–224). No significant correlations were obtained between the load factor and number of dwelling rooms in the present study unlike in Ref. (222), where a poor but positive correlation was found. However, in Ref. (222) the correlations were deduced for individual households which had almost similar load profiles unlike in the present case where correlations were deduced for a mix of individual and grouped households with significantly different load profiles. Both Ref. (222) and the present study found that occupant's characteristics greatly impacts the load demand profile.

Despite having similar capital and operation costs of the system, the LCOE for Case 57 (0.164 \$/kWh) was lesser than LCOE for PV-battery system observed in Chapter 3 and Chapter 4 where the type of load demand were academic township and grocery store respectively in the same location. This finding again suggests that different types of end-uses or load demand or applications have a significant impact on LCOE and system configuration due to variations in load profiles and demand. The LCOE variations among the three Sub-Categories within the residential sector in this study also highlight the significant impact of appliance user behavior, occupancy behavior and the consequent load demand variation on LCOE similar to Ref. (70,244,245). However, in this work, almost realistic scenarios have been investigated through innovative categorization, unlike the hypothetical scenarios in Refs. (70,244). The Refs. (70,244,245) and this case-study point towards the need for proper demand side management to reduce the LCOE and optimize the system configuration.

Both this case-study and Ref. (246) emphasized on the need for use of real data instead of assumption-based profiles as they lead to over-estimation of capacities and costs. However, the studies considered in Ref. (246) were for developed nations where real load data is more likely to be available due to availability of modern technologies like smart meters and reliable electricity unlike this case-study area, where generation of real time series load data on a household level was not practically possible at the time of investigation, due to which RAMP was used. In the present case, the average monthly load of 181.2 kWh/household, generated without considering power outages, may be an over estimation of the real load scenario in the location frequently impacted by power outages (247). But a location without power outage is the prime motivation of this investigation and thus the overestimated load is a likely futuristic scenario.

In this study, higher day-to-day variations in load demand increases the LCOE while in Ref. (246) higher day-to-day variations in solar radiation increases the LCOE. The present study conducted the analysis with fluctuating day-to-day demand and constant solar radiation conditions over a year while Ref. (246) conducted the analysis with the constant demand and fluctuating day-to-day solar radiation over a year. Thus, day-to-day variations in either load demand or solar radiation may significantly influence the LCOE and system configuration.

This study found that higher DOD for lead acid batteries resulted in lower LCOE similar to Ref. A BESS sizing strategy for primary frequency regulation support of solar photovoltaic plants(195,197), thus implying the need for effective utilization of batteries.

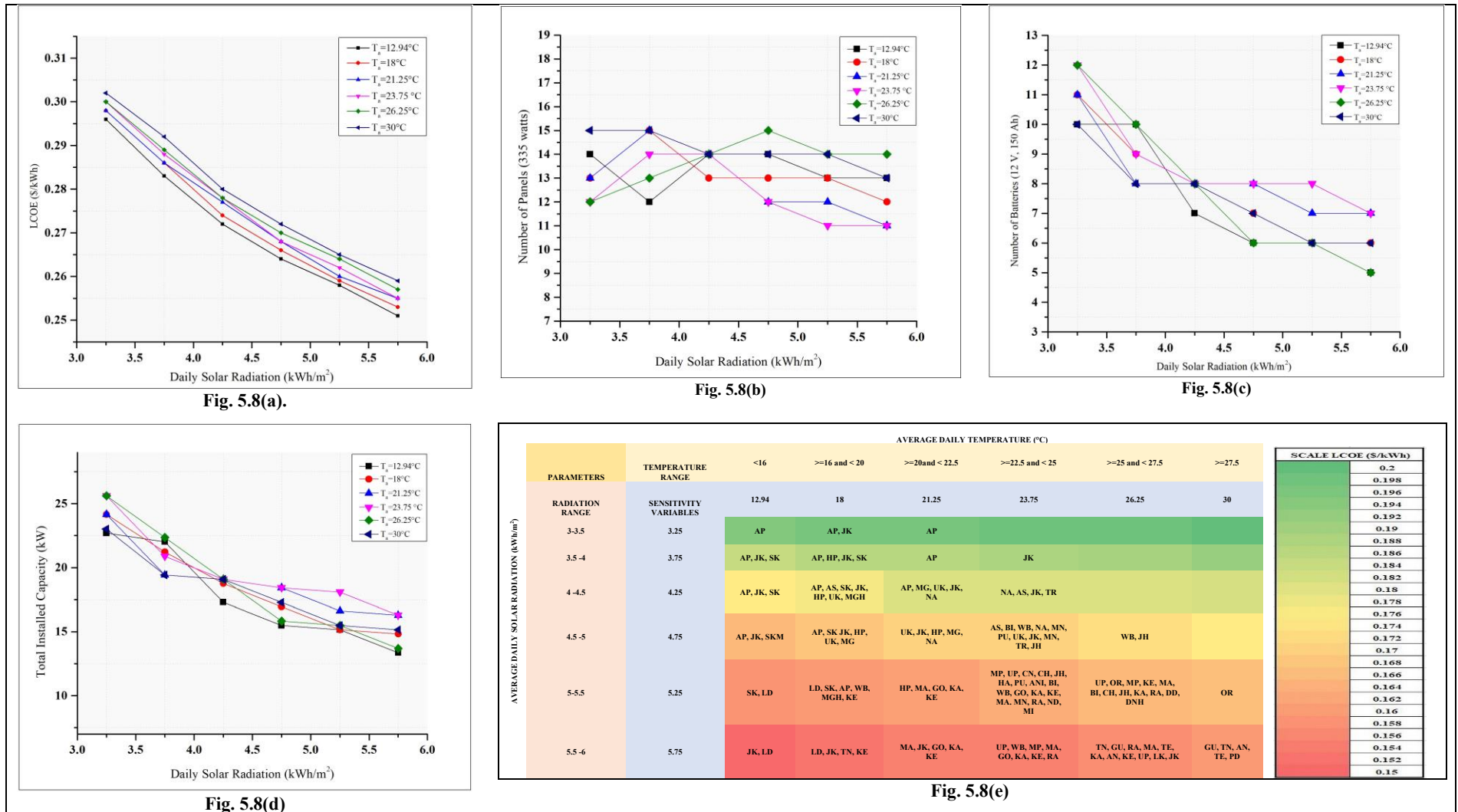


Figure 5.8 Impact of sensitivity parameters on the system outcome

(a) Impact of climatic conditions (solar radiation and ambient temperature) on LCOE (b) Impact of climatic conditions on quantity of solar panels (c) Impact of climatic conditions on quantity of batteries (d) Impact of climatic conditions on total capacity of PV and batteries and (e) Distribution of locations within states with respect to LCOE and climatic condition

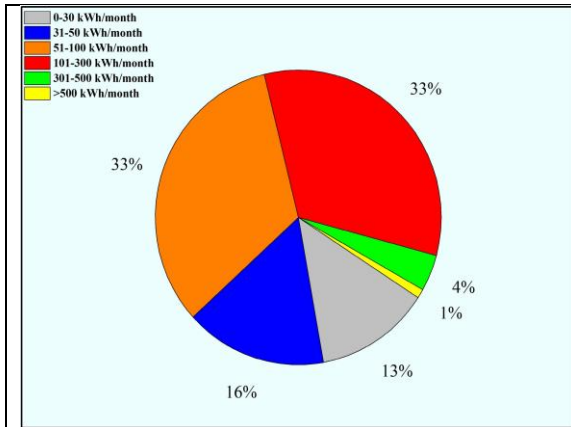


Figure 5.9 Percentage Distribution for Urban Households as per Monthly Load Demand in India

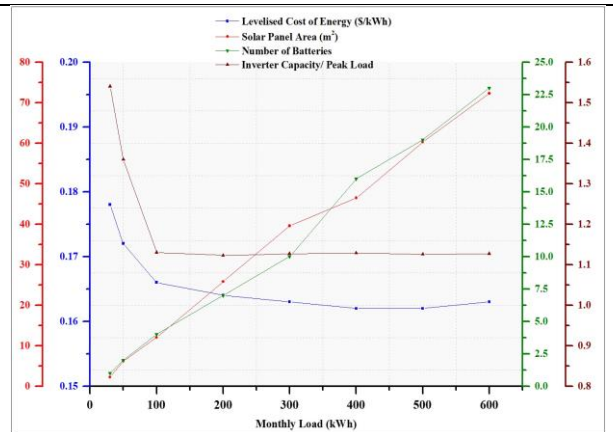


Figure 5.10 Impact of Monthly Load on Various Output Parameters of the optimized configuration system

In this study, locations with higher radiation and lower temperatures were found to be more promising for PV nanogrids in terms of cost and capacity similar to Ref. (245). However, in Ref. (245) the investigation was conducted for limited number of locations compared to the present investigation. This case-study also finds urban localities in Sikkim, fairly promising economically for PV nanogrids. However, exact investigations on a location-to-location basis may provide slightly different results as day-to-day variations in solar radiation and clearness index will vary across locations which will also impact the outcome (240,246,248).

In this study, the LCOE range of 0.151 \$/kWh to 0.195 \$/ kWh was higher than the grid tariff, similar to Chapter 3, Chapter 4 and (225). Apart from the high system capital costs, a poor capacity factor (249,250) range of 12.1%-22.5% for the solar panels across different locations of the country significantly contributed towards the higher LCOE as it indicates an underutilization of the solar panel's maximum potential mainly due to limited solar radiation reliability and availability. The excessive electricity production (65.7 %) with a significantly high renewable energy production compared to demand load (321%) also contributed towards the higher LCOE. Apart from a low load factor (0.31) and high day-to-day load variations, the misalliance of diurnal time durations of the highest panel electricity production duration (9:00 am-3:00 pm) with the peak energy demand duration (Fig. 5.5(g)) significantly contributed to this excess or unused electricity, like in Ref. (246). Due to a lack of sellback opportunity in an off-grid system, the system's electricity production remains unutilized which hinders any opportunity in further reduction of LCOE. The misalliance is significantly reduced via sharing of nanogrids among different types (Sub-Categories) of users which also reduces timestep and diurnal variations in load demand bringing more uniformity in the load profile and specifically for nanogrid users having relatively high demand load during the daytime (Sub-Category 3). However, continuous declining costs of solar panels (218) and batteries (251) accompanied by demand side management and rising grid electricity prices may lead to grid parity by next decade where off-grid PV systems may become affordable without subsidies.

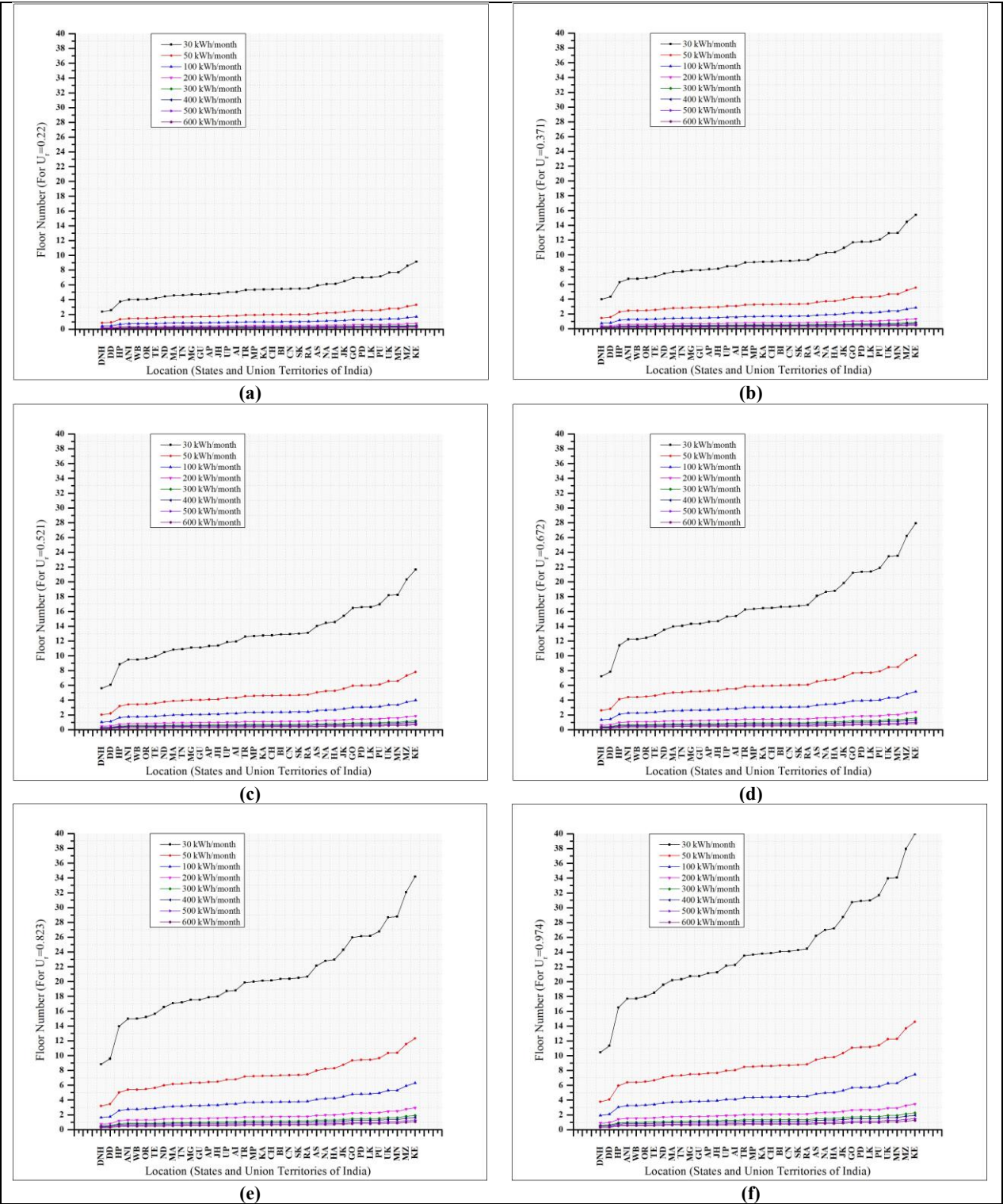


Figure 5.11 Impact of monthly load and effective roof utilization factor on the space feasibility number across various states and union territories of India

Chapter 6 Case-Study 4. Impact assessment of changes in appliance user behavior on configuration of an off-grid DES for electrification of a residential demand.

6.1 Introduction

An extension of the work done in Chapter 5; this analysis investigated the impact of change in load profile within a single household over a period of time on the techno-economic outcomes of the standalone rooftop PV nanogrid.

6.1.1 Problem

With the increase in ‘work from home’ culture due to Covid-19 pandemic, many people have started to stay at their residences for longer periods of time especially during the day period than before on weekdays. Similar changes also happen when people suddenly retire from their jobs and their residence time in their house increases. This has also led to change in the user behavior of the electrical appliances considerably in the day period than before in such households. In a location with unreliable electricity, if an off-grid renewable energy system (RES) has to be installed then the change in appliance user behavior may also impact the configuration of the system as already observed in Chapter 5. For this purpose, a techno-economic analysis is necessary as the off-grid systems should be able to provide continuous electricity without any unmet demand at the minimum cost possible. The techno-economic investigation for identifying any change in configuration of an off-grid RES with change in appliance user behavior has not been investigated before. In the present work, a techno-economic investigation has been conducted to identify the changes in the configuration of an off-grid RES with changes in the electrical load profile for a house with an unreliable electricity.

6.2 Methodology

HOMER Pro Microgrid Analysis Tool has been utilized to execute the analysis. Initially, “Optimizer” has been used to identify the rough installation capacities or size of the system. After deducing the rough capacities, “Search Space” has been used to determine the exact capacities or exact size of the system based on market sizes available for installation. The requisite inputs for HOMER Pro are deliberated in the subsequent sections.

6.3 Identification of Site

To clearly comprehend this investigation, three criteria were set for identification of the site prior to investigation. The first criterion involved the investigation of a residential load in an unreliable electricity area; as per the second criterion the household identified for generation of residential load should have all its members in occupation for at least two years during which for one year they have been out of their house on a daily basis during weekdays for at least 8 hours for almost the entire year and for another year they have been staying in the house on a daily basis for 24 hours a day for almost the entire year and as per the third criterion the household should be using the same appliances during the period of investigation. To satisfy the above three criteria, a household consisting of two people located at Borjhar area of Guwahati, Assam, India at “26° 5.5’N latitude, 91° 31.5’E longitude” was considered as the sample site for the investigation. The household stayed in a single storied house consisting of three dwelling rooms, two lavatories, one balcony and a kitchen. Both the members of the household were working in the software company. Prior to Covid both the people have to go to their office during weekdays and only got to stay at home during weekends except on holidays and vacations. After the onset of Covid, both the members have been working from home during weekdays for over a year. For this investigation the household’s appliance use behavior between the period from March 2019- April 2021. From March 2019 to February 2020, the household was going to office during weekdays while from May 2020 to April 2021, the members of the household were working from home during weekdays. During this entire period of investigation, the household has not bought any new electric appliance. Thus, the investigation period has been divided into two conditions as depicted in **Table 6.1**.

Table 6.1 Details of Condition considered for this investigation

Condition Number	Description
Condition 1	The residents are not available in the house for a minimum of 8 hours per day in the daytime during weekdays for almost the entire year
Condition 2	The residents are available in the house throughout the day during weekdays for almost the entire year

6.4 Generation of Demand Profile for the Conditions

Though the monthly electricity bills were available for the household but the exact hourly load data was not available as there was no smart meter available in the house. To get load data in close proximity to real time load of the household and in a shorter period of time, a load profile generator called RAMP (176) has been used for this investigation. The details of the equipment used in the household and a sample of input details necessary for the RAMP software have been provided in **Table 6.2** and **Table 6.3** respectively.

Table 6.2 Details of Appliances Used in the House

Appliance Name	Appliance Code	Rated Power of the Appliance (Watt)	Quantity
Fluorescent Tube light 1	A1	55	6
Fluorescent Tube light 2	A2	40	1
LED Bulb1	A3	9	3
Hair Timmer Charger	A4	5	1
Hair Drier	A5	1000	1
Ceiling Fan	A6	70	3
Exhaust Fan1	A7	55	1
Exhaust Fan2	A8	40	1
Television	A9	60	1
Set Top Box	A10	10	1
Refrigerator	A11	12	1
Washing Machine	A12	600	1
Vacuum Cleaner	A13	1000	1
Laptop	A14	60	2
Microwave Oven	A15	6	1
Mixer Grinder	A16	500	1
Water Purifier	A17	60	1
Iron	A18	1200	1
Water Pump	A19	500	1
Bathroom Geyser	A20	2000	1
Kitchen Geyser	A21	2000	1
Room Heater	A22	800	1
Phone Charger	A23	5	4
Mosquito Repellent	A24	7	3
Music System	A25	200	1

6.5 Resource Availability

The solar resource potential data was directly imported via HOMER PRO from NREL, USA database. The selected location has a considerably attractive solar energy potential with an average annual radiation of 4.55 kWh/m²/day. The least solar radiation per day was observed in July with an average value of 3.798 kWh/m²/day while the highest radiation was observed in April with an average value of 5.851 kWh/m²/day The site has the least clearness index in the month of July with a value of 0.378 which peaked to 0.640 in the month of December. The location has a moderate temperature with an annual average of 23.44^oC which peaked to 28.8 ^oC in the month of June and dipped to 14.88 ^oC in the month of January. The details of resource potential for the location have been depicted in **Figure 6.1** and **Figure 6.2** respectively.

Table 6.3 Details of inputs required for RAMP software for the month of June

Appliance Code	t_{max}	t_{min}	t_{maxvar}	N_{wind}	$t_{start,wind}$	$t_{end,wind}$	$t_{wind,var}$
A1	2-6	15	15%	1	6:00 PM	12:00 PM	10 %-30 %
A2	3	15	15%	2	6:00 AM	8:00 AM	20 %
A3	1.5	5	20%	2	8:00 PM	11:00 PM	20 %
					12:00 AM	9:00 AM	10 %

A4 (occasional use)	8	15	15%	2	6:00 PM	12:00 AM	10 %
					6:00 PM	12:00 AM	30 %
A5 (occasional use)	0.25	15	15%	1	12:00 AM	12:00 AM	30 %
A6	6-12	15	15%	2	6:00 AM	6:30 AM	10%
					6:00 PM	12:00 AM	20%
A7	1.5	5	20%	2	12:00 AM	9:00 AM	20%
					6:00 PM	12:00 AM	10%
A8	2	15	15%	2	12:00 AM	9:00 AM	20%
					6:00 AM	8:00 AM	20%
A9	4	30	20%	1	7:00 PM	11:30 PM	20%
A10	4	30	20%	1	6:00 PM	12:00 AM	15%
A11	24	45	0%	1	6:00 PM	12:00 AM	15%
A12	0.5	30	10%	2	12:00 AM	12:00 AM	0%
					6:00 AM	8:00 AM	15%
					6:00 PM	11:00 PM	15%
A13	0.5	5	20%	1	6:00 AM	8:30 AM	15%
A14	2	30	15%	2	6:00 AM	8:00 AM	10%
					6:00 PM	12:00 PM	10%
A15 (occasional use)	0.5	15	20%	2	6:00 AM	9:00 AM	15%
					6:00 PM	10:00 PM	15%
A16 (occasional use)	1	15	15%	2	6:00 AM	8:30 AM	30%
					6:00 PM	10:00 PM	30%
A17	1	30	15%	2	6:00 AM	8:30 AM	30%
					6:00 PM	10:00 PM	30%
A18 (occasional use)	0.5	15	15%	2	6:00 AM	8:30 AM	30%
					6:00 PM	10:00 PM	30%
A19	0.5	15	15%	2	6:00 AM	8:30 AM	30%
					6:00 PM	10:00 PM	30%
A20	-	-	-	-	6:00 AM	8:30 AM	30%
A21	-	-	-	-	6:00 PM	10:00 PM	30%
A22	-	-	-	-	-	-	-
A23	1.5	15	30%	2	6:00 AM	8:00 AM	35%
					6:00 PM	12:00 PM	35%
A24	5-10	30	15%	2	6:00 PM	12:00 AM	35%
					12:00 AM	6:00 AM	35%
A25 (occasional use)	1	15	25%	1	6:00 PM	11:00 PM	30%

6.6 System Design

The system component modelling of various system components was done in HOMER PRO using Eq. 2.1-Eq. 2.2 for solar panels, Eq. 2.11 – Eq.2.17 for batteries and Eq. 2.18-Eq. 2.20 for converter while economic modelling was done using Eq.2.21- Eq. 2.24.

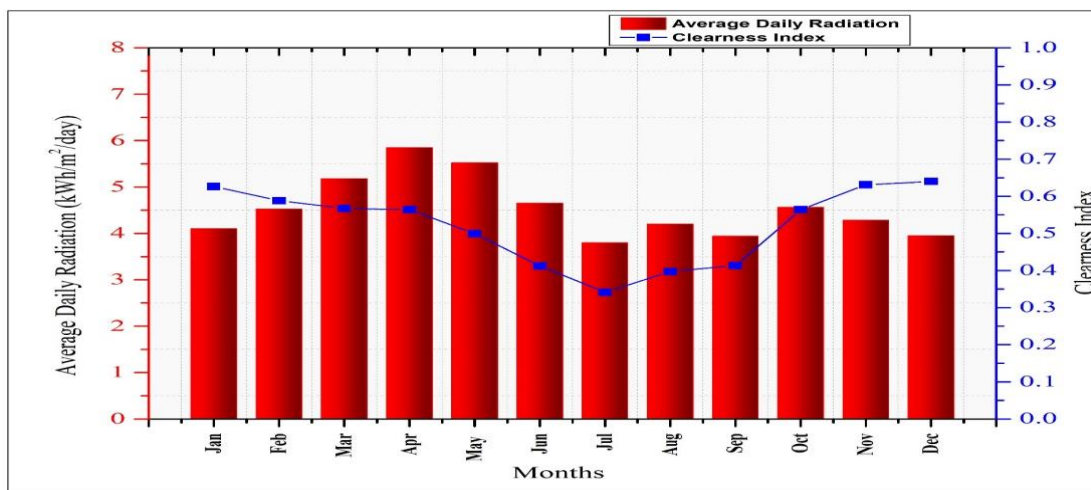


Figure 6.1 Solar Radiation Data

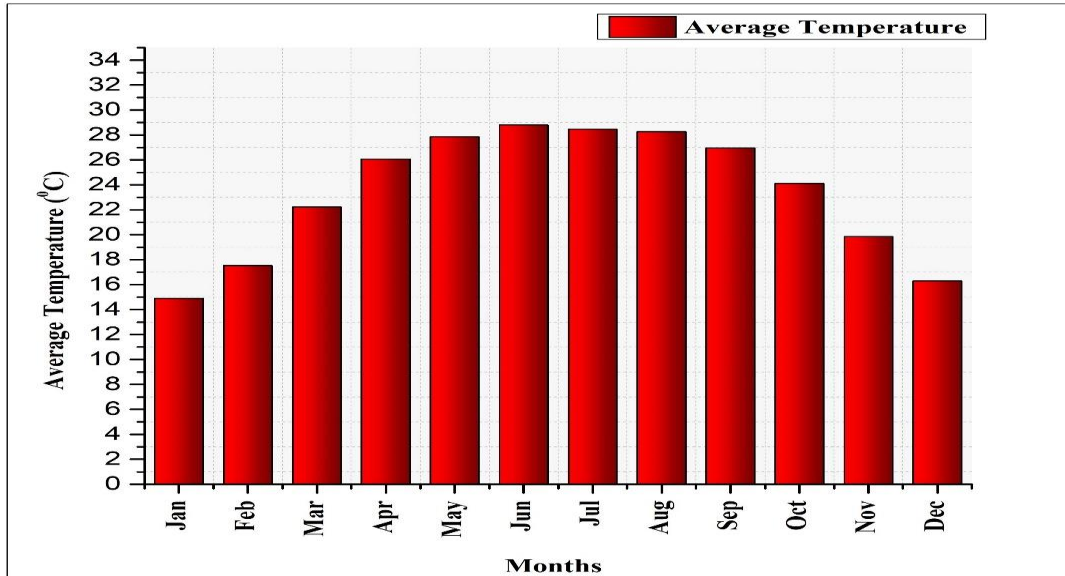


Figure 6.2 Temperature Data

6.7 Technical and Economic Specifications of Various Equipment of the HRES

The technical and economic specifications of the various equipment were taken from local market through quotations and provided in **Table 6.4** and **Table 6.5**. The average inflation rate was considered to be 3.5 % and discount rate was considered to be 8% and the project period was considered to be 25 years.

Table 6.4 Technical Specification of Component

Component	Parameter	Value
PV System (50,190,212,214)	Rated Capacity of each PV module(E_{RPV})	330 W
	Derating Factor(g_{PV})	88 %
	Nominal Operating Cell Temperature($T_{c,NOCT}$)	44°C
	Temperature Co-efficient(β_p)	-0.41 %/°C
	Efficiency at Standard Conditions(η_c)	17.01 %
Battery (50,212,213)	Rated Capacity	1.8 kWh
	Round Trip Efficiency	85 %
	Minimum State of Charge	20%
	Rectifier Efficiency	98.7 %
Converter (50,212,213)	Rated Capacity	600 Watt
	Inverter Efficiency	98.3%
	Rectifier Efficiency	98.7 %

Table 6.5 Economic Specification of Component

Component Details	Capital Costs (\$)	Replacement Costs (\$)	Operation & Maintenance Costs (\$)	Component Life
PV System (50,212,213)	459/kW	459/kW	10/year	25 yrs
Battery (50,212,213)	216.78/battery	160.47/battery	5/year	5 yrs
Converter (50,212,213)	65/kW	65/kW	10/year	15 yrs

6.8 Results

6.8.1 Generation of Load Data Using RAMP for Condition 1

The high-resolution load data generated through RAMP for all months were imported into HOMER Pro to generate the final load data for the entire year. A sample load profile generated by RAMP for Condition 1 has been provided in **Figure 6.3** and the annual load profile generated by HOMER PRO has been provided in **Figure 6.4**. The average load per day for the entire year was 7.27 kilowatt-hour (kWh) with an average load of 0.3 kilowatt (kW) and a peak load of 6.45 kW. The load factor for the demand was 0.05. The day-to-day random variation was found to be 10.07% while the random variation on a time step basis of a minute was found to be 101.83%. The peak month was found to be December.

6.8.2 Generation of Load Data Using RAMP for Condition 2

A sample load profile generated by RAMP for Condition 2 has been provided in **Figure 6.5** and the annual load profile generated by HOMER PRO has been provided in **Figure 6.6**. The average load per day for the entire year was 9.48 kWh with an average load of 0.4 kW and a peak load of 5.46 kW. The load factor for the demand was 0.07. The day-to-day random variation was found to be 20.596% while the random variation on a time step basis of a minute was found to be 91.685%. The peak month was found to be January.

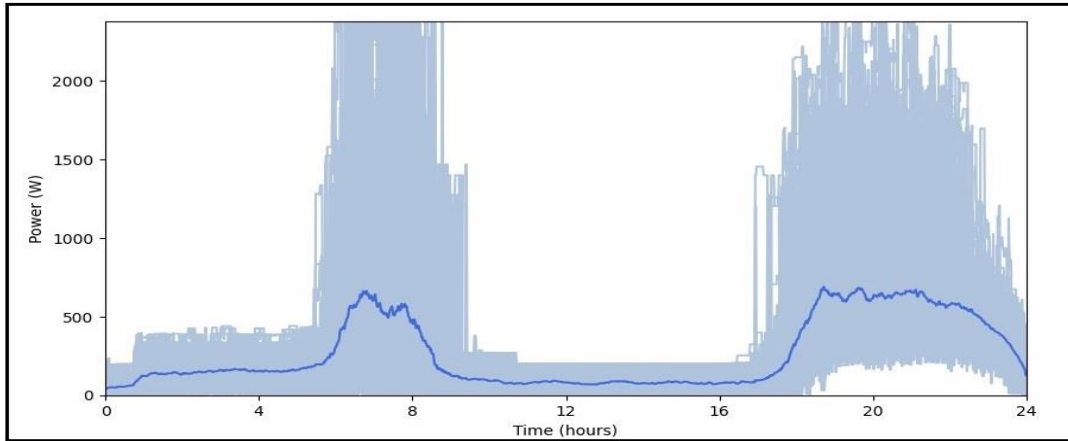


Figure 6.3 Load Profile Generated for weekdays for the month of June through RAMP for Condition 1

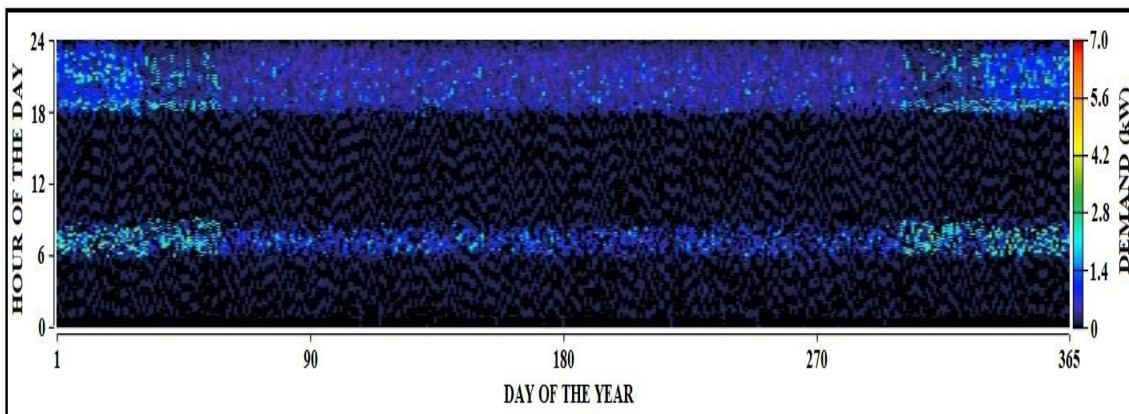


Figure 6.4 Load Profile Generated through HOMER for the entire year for Condition 1

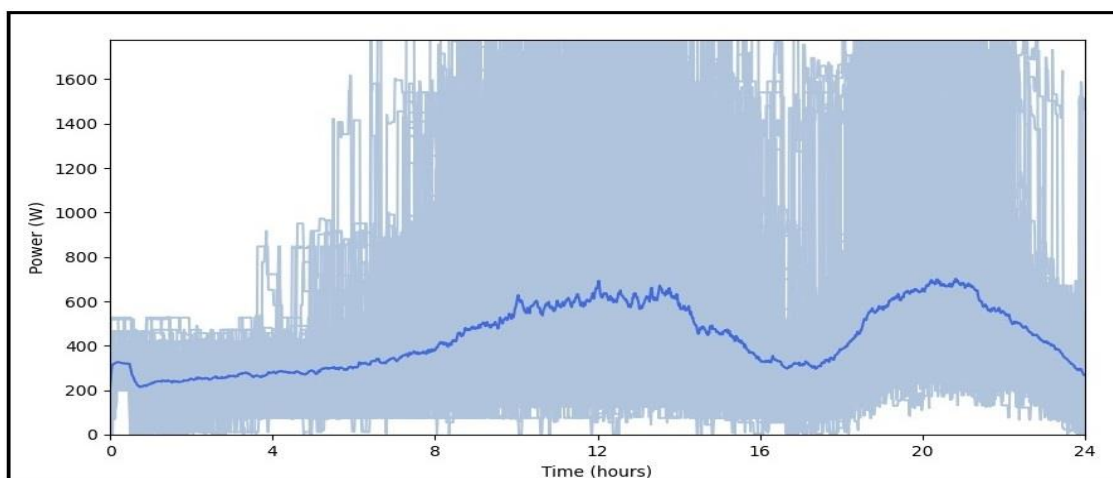


Figure 6.5 Load Profile Generated for weekdays for the month of June through RAMP for Condition 2

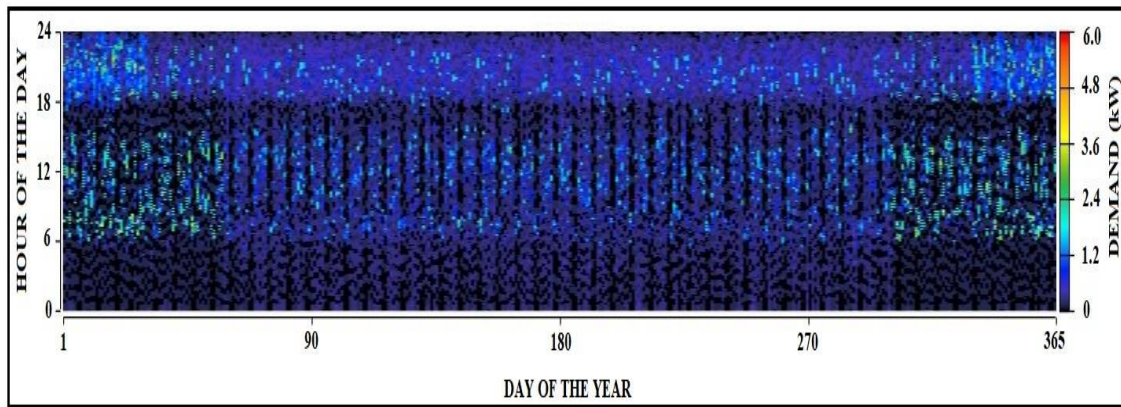


Figure 6.6 Load Profile Generated through HOMER for the entire year for Condition 2

6.8.3 HOMER PRO Simulation Results

Simulations for the two conditions were conducted with the collected economic and technical database on a time step of one minute for deduction of net present cost (NPC) in US Dollars (\$) and Levelized Cost of Energy (LCOE). The corresponding results obtained have been provided and discussed in following sub-sections.

6.8.3.1 Condition 1

The optimum configuration of the PV-Battery system for this Condition required 18 PV panels of 330 Watts each, 13 batteries of 12 Volts (V), 150 Ampere-hours (Ah) each and 11 converters of 600 Watts each. The NPC of the system was 16282 US \$ with the LCOE as 0.407 \$/kWh. The breakup of the total component cost of the system has been provided in **Table 6.6**.

Table 6.6 Break up of total cost of PV-Battery System for Condition 1

Component	Capital Cost (\$)	Replacement Cost (\$)	Operation and Maintenance Cost (\$)	Fuel Cost (\$)	Salvage Cost (\$)	Total Cost (\$)
Battery	2042.95	7081.87	1958.22	0	495.94	10587.10
Converter	924.00	394.96	994.17	0	239.14	2073.50
PV Panel	2726.46	0	894.76	0	0	3621.22
Total System	5693.41	7476.33	3487.15	0	735.08	16281.82

6.8.3.2 Condition 2

The optimum configuration of the PV-Battery system for this Condition required 52 PV panels of 330 Watts each, 22 batteries of 12 V, 150 Ah each and 13 converters of 600 Watts each. The NPC of the system is 33231 US \$ with the LCOE as 0.313 \$/kWh. The breakup of the total component cost of the system has been provided in **Table 6.7**.

Table 6.7 Break up of total cost of PV-Battery System for Condition 2

Component	Capital Cost (\$)	Replacement Cost (\$)	Operation and Maintenance Cost (\$)	Fuel Cost (\$)	Salvage Cost (\$)	Total Cost (\$)
Battery	3457.30	13960.59	3313.92	0	361.83	20369.97
Converter	1092.00	466.18	1174.93	0	282.62	2450.50
PV Panel	7876.44	0	2584.85	0	0	10461.29
Total System	12425.74	14426.77	7073.70	0	644.45	33281.76

6.9 Discussion

A comparison of load profile between condition 1 and condition 2 showed that condition 2 had higher load factor and average daily load while condition 1 had higher peak load by almost 40%. The reason for higher load factor and higher daily load demand for the condition 2 is due to more use of appliances during the day period from 9:00 AM. to 5:00 P.M on weekdays compared to condition 1. A higher peak load for condition 1 as compared to condition 2 is due to higher possibility of overlapping of more appliance usage in a shorter period of time in condition 1 as compared to condition 2. The NPC for condition 2 was higher than the NPC for condition 1. The increase in average and peak loads for

Condition 2 increased the capacity requirements of the nanogrid system which increased its NPC. However, the LCOE for Condition 2 was found to be lesser than Condition 1 as the percentage day-to-day variations was lower for Case 2 when compared to Case 1 which may have resulted in a lower LCOE for Condition 2 when compared to Condition 1, a finding similar to Chapter 5. Further the Load Factor for Condition 2 was higher when compared to Condition 1 which also contributed to the lower LCOE of Condition 2. Hence, despite a higher NPC, the LCOE for the system for “work from home” condition was lesser compared to “work from office” condition.

Chapter 7 Case-Study 5: Modeling of a rooftop solar photovoltaic system for electrification of a public school.

7.1 Introduction

Chapter 7 extends the investigation done in Chapter 4 for “market sector” and Chapter 5 for “residential sector” to the “academic sector” which is also a dominant load contributor in the almagamated load profile in Chapter 3 for the “academic township”. However, in place of a higher education academic institute, we extend our investigation for a public school. Further, this chapter extends the investigation from standalone configuration to grid-tied configurations.

7.1.1 Problem

The grid unreliability is a major concern in India which affects all sectors, including schools (195–197) with frequent power outages can detrimentally impact the teaching quality, student growth and ultimately student enrolment (198–200) . Many schools choose to employ expensive and environmentally polluting DGs while many remain without back-ups (199). To enhance the student enrolment in schools and maintaining the nutritional level of students, the Government of India also implemented PM-POSHAN scheme (previously known as Midday meal scheme) which has been reasonably successful in the past (201–204). However, lately the cooking of mid-day meal has become unsustainable economically with the rising LPG cylinder prices being a major contributor (205) .

Consequently, many public schools in India use firewood for cooking midday meals (206) which poses serious health risks and cause environmental degradation (207–210). Further, the fact that the popular LPG itself is a non-renewable energy source and a moderate green-house gas emitter cannot be overlooked in the future (210–212). E-cooking may be a viable alternative to combat both the rising prices of LPG and the negative effects of traditional method of cooking on people’s health and the environment. However, introduction of e-cooking will burden the already unreliable centralized grid and may further impact the enrolment of students in schools. Hence, Decentralized Energy Systems (DESSs) can be viable alternatives, either as compliment to the grid or as replacements. DESSs produce energy locally close to the place of end-use and generally utilise renewable energy resources (13,53,213) and can collaborate with central grids also (13).

The grid unreliability amplifies in the complex terrain of Himalayan states like Sikkim (13,195). Despite, Sikkim being a renewable resource rich state (121,195), their implementation is limited by issues related to economic feasibility, area availability and environmental regulations (8,10,12,13,15,16,19,195,214). In schools, most of the ground area is taken up by playgrounds and parking lots which makes RTPVS a prospective alternative (195,215) as the functioning hours of the school (8:00 am-4:00 pm) coincides with the time window of solar radiation (215). Successful implementation of an RTPVS may help in fulfilling United Nations Sustainable Development (UNSDG) goal 7 (Affordable and Clean Energy) which may ultimately help in fulfilling three other goals like UNSDG 2 (Zero Hunger), UNSDG 4 (Quality Education) and UNSDG 13 (Climate Action) (216). Hence a techno-economic-space feasibility investigation is necessary in this regard.

RTPVSs can be of three types, namely, standalone configuration comprising of PV and battery as back-up (PV-battery), grid-tied configuration without battery back-up (PV-grid) and grid-tied configuration with battery backup (PV-grid-battery). Standalone systems can be expensive for low load factor load profiles (67) compared to grid-tied systems. However, in unreliable grid locations, an important issue persisting with PV-grid configuration with traditional grid-tied converters is that the PV panels are cut-off by the converter from the demand and the grid during grid outages for the safety of linesman or utility workers repairing the grid and thus the demand remains unmet (276–278). However, for PV-grid-battery configuration, during outages the batteries can be used to meet the demand when the PV panels are cut-off during grid outages. The use of only batteries for meeting demand during outages, however, can make the system expensive. Recently developed smart or advanced hybrid converters can make the PV-grid-battery configuration act like a standalone system instantaneously

during outages and PV can meet the demand (276,279). This technology though, currently not available for only PV-grid, may evolve in future with further improvements in voltage and frequency synchronization. However, these configurations can be expensive due to the very high cost of these new advanced converters. Thus, considering the boons and cons of the different configurations and their Dispatch Strategies (DSs), an overall investigation of these configurations and strategies is necessary to understand which configuration and which DS shall be best option for powering the school.

7.1.2 Salient Literature Reviews in the context of the case-study

Techno-economic investigations are location-specific and application-specific due to variation of the input data with location and application (50,53,219). Some of the salient literatures and their key findings in the context of the present work are detailed in Table 7.1.

Several software tools (50,183–185,220–222), conventional optimization techniques (223) and meta-heuristic techniques (223–226) are available for conducting techno-economic-space feasibility investigations involving PV microgrids. A very prominent, robust, user-friendly and dedicated software tool for techno-economic analysis is HOMER PRO which has been used for both research and commercial purposes in practical projects worldwide. A financial optimizer, HOMER PRO deduces all the ‘feasible’ DES configurations including the cheapest one that can meet the demand. It performs complex sensitivity analysis by varying the input parameters thus generating outcomes that can lead to policy decisions. HOMER PRO can also model complex grid outages (50,183,184) for grid-connected systems, employ a variety of Dispatch Strategies (DSs). However, HOMER PRO is not directly able to determine whether a system like RTPVS has sufficient area available for installation. Further it does not take shading losses into account which makes the analysis approximate. HOMER PRO can compensate for this limitation by direct or indirect importation of data from another software called PVsyst (50,184,185,222).

Table 7.1 Salient Literature Reviews

Ref.	Photovoltaic Systems for Schools
(199)	Designed an off-grid PV-battery microgrid for an Ethiopian rural school, for load estimated with standard and energy-efficient appliances and found that the energy-efficient appliances reduce the system cost.
(227)	Experimentally deduced a PR of 0.78 for grid-connected RTPVS in three Palestinian schools.
(228)	Investigated the impact of PV module type on performance of grid-connected RTPVS for an Algerian school and found that Demand Side Management (DSM) increases RTPVS’s power injection into grid.
(229)	Designed an off-grid PV-battery-DG hybrid system for a Bangladeshi school; found significant reductions in LCOE and Green House Gas (GHG) emission than conventional power plants.
(230)	Experimentally deduced a PR of 0.7-0.85 for grid-connected RTPVSs in Kuwaiti schools; found that panel cleaning enhances PR.
(231)	Found that limited capacity grid-connected RTPVSs in Iranian schools are economically incompetent even under subsidized average tariffs as the small capacities prevent grid sales.
(232)	Experimentally deduced a PR of 0.78 for a grid-connected photovoltaic system (PVS) in New Zealand school and also observed significant grid purchase reduction.
(294)	Conducted a techno-economic analysis of using HOMER PRO for an off-grid DC PV-battery system for a school in Roorkee, Uttarakhand. The cooking demand was separately met by solar thermal application whose motors for disc tracking were powered by the DC system. Also conducted experimental analysis on a reduced scale to investigate the technical performance.
Unreliable grid	
(233)	Conducted feasibility analysis of a grid-connected RTPV-battery-DG system for an Indian urban private school with unreliable grid; conducted the technical planning of PV panels with Solar Labs and PVsyst software and economic analysis with HOMER software and Excel sheet-based financial models; proposed an innovative DS to reduce grid and DG electricity consumption during power outages and reduce peak demand below maximum billable demand.
(234)	Conducted techno-economic analysis for grid-connected PVS with different battery technologies for unreliable grid and found batteries with different lifetime and capital costs economically suitable for different grid outage frequencies.
(235)	Analyzed the techno-economic-environmental viability of a grid-tied PV microgrid which supplies the demand during both grid availability and outage periods.
RTPVS	
(217)	Conducted a comprehensive investigation of RTPVS’s economic, area and environment potential in Hong Kong and found it expensive at that time due to high installation costs.
(138)	Conducted a techno-economic investigation of a PV-battery-time constrained grid system for electrification of an Indian village using HOMER. Shifting of non-essential loads from peak time reduces the LCOE.
(218)	Conducted techno-economic analysis for grid-tied RTPVS in three Indonesian cities and concluded that location-based incentives on installation area limit and net-metering rates are necessary for their viability.

- (236) Deduced the RTPVS potential for two UAE cities and found the net metering policy useless as total demand was much higher than the RTPVS output which resulted in very high LCOE despite subsidies.
- (237) Conducted a techno-economic investigation of grid-tied PV-Battery System in China and found that the system reduces LCOE in commercial buildings (due to subsidies) and increases it in residential buildings. The battery input parameters (capital costs, lifetime) have more effect on LCOE than PV.
- (238) Compared the experimental and HOMER PRO simulated performance of a grid-connected RTPVS on a Malaysian University building; HOMER PRO yielded reliable results when experimental PR was used and equipment failure was not considered.
- (239) Proposed an innovative Energy Management System (EMS) Algorithm for a grid-tied PV-battery system in an Egyptian University that minimizes grid consumption by 40 % and is validated using PVsyst simulation and lab experiments.
- (140) Found a significantly higher PV self-consumption for university building than residential building while investigating a grid-tied RTPVS with battery storage.
- (240) Optimized the installation parameters such as tilt angle, pitch, gain factor, altitude angle and shading for an RTPVS with PVsyst to significantly improve the energy yield and installation capacity for a given area in Mumbai, India.

E-Cooking (Key findings)

- (241) E-cooking has higher capital cost and lower operational costs and emissions than fuelwood.
 - (242) E-cooking quadruples the monthly bills over base load though DSM halves it for grid.
 - (243) Investigated the techno-economic impact of e-cooking addition on base load for an off-grid PV-battery microgrid for residential community and a small community service centre and found very negligible changes in LCOE for both the cases when compared to the base case.
 - (244) E-cooking significantly reduces kerosene and fuelwood usage in Bhutan thus reducing emissions.
 - (245) E-cooking can economically and environmentally compete with LPG and charcoal in grid-connected households in Rwanda.
 - (304–306) Investigated the impact of partial and complete penetration of E-cooking over residential demand for 108 households in African countries by modelling the E-cooking demand with CREST tool and conducting techno-economic analysis with grid and standalone microgrids comprising of PV/ Diesel Generator (DG) and found the main barriers to be high LCOE of E-cooking for both grid and standalone microgrids and insufficient generation capacity to meet the combined demand of E-cooking and normal demand for standalone microgrids.
-

A technical optimizer, PVsyst can determine the space or area requirements of a particular configuration of RTPVS by estimating the maximum number of panels that can be fitted in a particular area by providing a diagrammatic representation of the exact positioning of PV panels and also provide accurate values of optimum tilt angle, azimuth angle, pitch and derating factor or PR for the highest or optimum PV output of a particular configuration at a particular location by including shading losses and electrical aspects into account (183,220,222). PVsyst can also conduct economic analysis, though, limited in terms of economic sensitivity analysis and economic design customization compared to HOMER PRO.

A few literatures have combined PVsyst and HOMER PRO for conducting performance analysis of PV systems (307–309) where the pre-sizing of panels was done on the basis of “required power or demand” in PVsyst.

Another limitation of HOMER PRO is that for grid-connected RTPVSs, its in-built DSs can cut-off the PV panels from the grid but not from meeting the demand load during grid outages even for RTPVSs without any battery back-ups. This type of DS can be performed only by recently developed expensive advanced smart hybrid converters which can almost instantly isolate the entire RTPVS from the grid during outages and PV panels can meet the demand safely like batteries; however, battery back-ups are mandatory in such systems in practise. But the use of cheaper traditional hybrid inverters and grid-tied inverters, which cut-off the PV panels from the both the grid and the demand (184,276) during grid outages due to safety regulations (276–278) are still practically prevalent compared to the expensive alternate arrangements like advanced hybrid converters in most developing countries. HOMER PRO compensates for this limitation by allowing interfacing with MATLAB to formulate customized and novel DSs that can cut-off the PV panels from both the grid and the demand load during outages (184,276). This formulation will help to understand the advantages and disadvantages of both the upcoming advanced hybrid converters that HOMER PRO already employs and the traditional grid-tied and traditional hybrid converters still prevalent in developing countries.

Modelling load profiles in the absence of real times series load data is another issue (178,179) which has been addressed by recently developed techniques and software such as RAMP, LOAD PRO Gen, CREST tool etc. (176,177,180) which generate load profiles based on survey in very closed

proximity to real load data and thus help in optimum microgrid design. The accuracy of these software still depends on the input parameter details provided by the survey data.

7.1.3 Research Gaps, Objectives and Novelty

The identified research gaps based on the literature review are detailed below:

- The techno-economic feasibility investigations rarely consider maximum area available for installation as a constraint during the investigations for designing RTPVS for various types of load demand. The area requirement for installation of a modelled system is a critical issue as it will require additional capital costs for purchase of land or rooftop leasing if the techno-economically designed system does not have sufficient area available for installation.
- Techno-economic-space feasibility of an RTPVS has not been conducted in space-constrained public schools prevailing in complex hilly terrain and outage ridden North-Eastern Indian states like Sikkim.
- Most of the previous investigations on e-cooking have considered very small scale of demand limited to 15 households or a very small community not exceeding 30 people and over a more distributed load profile for the day. However, the impact of sudden addition of a large e-cooking load of about 500 persons, onto the existing load which itself is limited to few hours of the day, needs further investigation.
- The impact of grid unreliability on the grid-tied RTPVS performance with or without battery back-up, especially the comparative analysis between two scenarios where the PV is islanded from the demand or continue meeting the demand when the grid is in outage is necessary. There is a scope for development of customised DSs in this context using the MATLAB-HOMER PRO link. Further the impact of prohibition or permission of grid sales from battery or PV panels needs investigation.
- It is also important to understand how such a modelled system will perform economically across schools available in different climatic conditions in India.

Hence, the objectives of this work are to:

- Conduct a techno-economic-space feasibility investigation for 3 RTPVS configurations namely, standalone PV-battery, PV-grid and PV-grid-battery, for electrification of a school in the grid outage ridden state of Sikkim, India with the help of PVsyst and HOMER PRO.
- To deduce the optimum PR and maximum capacity of panels on school rooftop using PVsyst.
- Model the existing demand, e-cooking demand and energy-efficient demand via RAMP software and investigate their impact on the system performance, configuration and costs.
- Model complex grid outages in HOMER PRO and to implement 5 DSs comprising of three in-built HOMER PRO DSs and two innovatively developed DSs via MATLAB-HOMER PRO and investigate the impact of permission or restrictions on transactions among PV panels, battery and the grid to meet the demand during grid outages by comparing the DSs.
- Compare the modelled system with the existing energy supply configuration in the school and with the prevalent grid-battery configuration.
- Conduct reliability analysis and sensitivity analysis for various input parameters with an emphasis on grid unreliability to comprehend the system behaviour on a broader perspective.

The novel contributions of the present work are:

- The investigation was conducted in space-constrained and grid-outage ridden North-eastern Himalayan territory for the first time for this type of load profile.
- Modelling of a large-scale e-cooking demand apart from the existing electric demand and the consequent techno-economic performance evaluation in an Indian public school. In addition, impact of replacing frequently used appliances with energy-efficient appliances is also investigated. To fully comprehend the impact, additional unsubsidized capital costs incurred in replacements of existing cooking and electric appliances with energy-efficient appliances and e-cooking appliances was also considered.

- Development of two innovative DSs in MATLAB and implementation with HOMER-MATLAB link, one each for PV-grid and PV-grid-battery to comprehensively investigate the system performance during grid outage.
- Implementation of a more precise upper limit of panel capacity and optimum PR value deduced via PVsyst in place of corresponding assumed values generally used in HOMER PRO during the techno-economic space feasibility investigation to provide a more conservative and realistic outcome.
- A comprehensive investigation of different DSs for PV-battery-grid configuration which either allow or prohibit grid sales from PV or battery.
- Use of RAMP for modelling the load demand in the absence of time-series load data for the school in place of non-stochastic assumption-based load demand and modelling of a complex grid outage scenario with both planned and random outages and detailed investigation of impact of grid outages on system results and configurations for grid-tied PV systems.
- Critical investigation of impact of inverter capacity on LCOE for grid-tied PV systems.
- A comprehensive deduction of LCOE for such a load profile across different climatic conditions of India using sensitivity analysis for countrywide policy implications.

7.2 Methodology

The methodology flowchart has been depicted in **Figure 7.1**.

7.2.1 Software Selection

The economic feasibility analysis was conducted using HOMER Pro software due to its prominence, robustness, high computational efficiency and user-friendliness. The time series load demand of the school required for HOMER PRO was generated using RAMP. The optimum values of tilt angle, azimuth angle, the pitch and the PR (245) and the maximum number of panels that can be installed were calculated using PVsyst software prior to HOMER PRO analysis. MATLAB was used to formulate two innovative DSs for HOMER PRO during the grid outages.

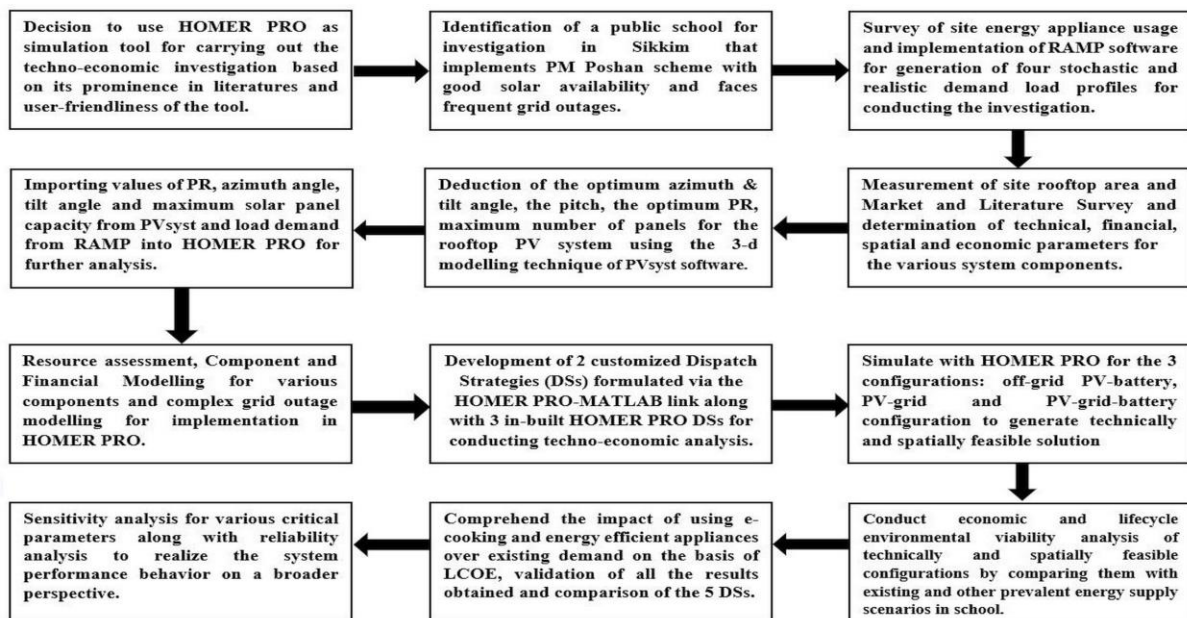


Figure 7.1 Flowchart of the methodology used

7.2.2 Site Selection

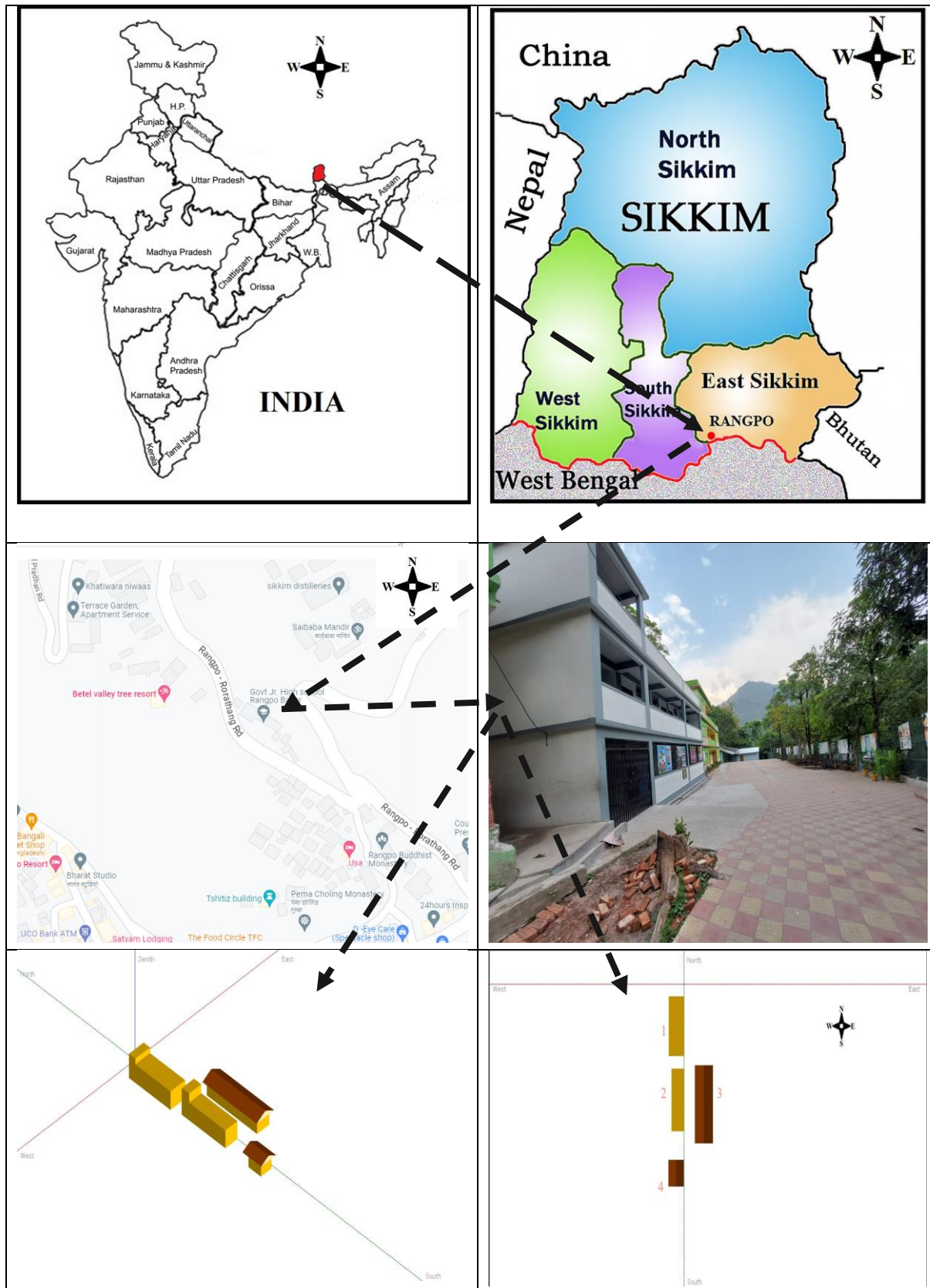


Figure 7.2 Location of the school (250–252)

The case-study location was Rangpo suburb of Pakyong district, Sikkim, India with a substantial cosmopolitan population (**Figure 7.2**). Due to the continuous industrial development and

the consequent residential and commercial development in the location, the State Power Department has been unable to tackle the increasing electric demand resulting in regular planned and random unplanned outages (195). Apart from that the calamity prone region also experiences weather-induced outages which are very tedious to repair. In October 2023, the lower parts of the location had to encounter significant damage to property and lives due to flash floods caused by glacial lake outburst on the Teesta River, further amplified by the consequent Chungthang mega hydropower dam burst used to meet the energy demands of the location via grid (248,249). The selected school was a public secondary school, named, Rangpo Bazaar Government Secondary School, in Chanatar area of Rangpo, located at 27.17 latitude, 88.53 longitude. It was selected because of easy access to appliance data, a relatively multicultural student and faculty composition, sound student strength, infrastructure and area availability like other public schools in India, its regular experience of grid outages and a dedicated implementation of PM-POSHAN scheme (202). A questionnaire based-survey was conducted to collect primary data after the school authorities agreed to co-operate with the work and the entire data was collected in 5 visits over a period of 2 months. The rooftop and base area of the school was measured physically. The school had 2 main buildings with flat roofs, a new building with tilted roof (under construction) and the shed (security office and canteen/mess) with tilted roof. The shed (Building 4) was also under maintenance and was planned to be cut down to a rectangular layout from the existing L-shaped layout to increase the school entrance width and the canteen/mess is planned to be shifted to Building 3 once the construction is complete (**Figure 7.2**). The total measured roof area of the available and modified buildings was 602.52 m² (**Table 7.2**). The school used two rooms for storing obsolete items like furniture and documents prior to auctioning. The school consisted of 597 students, with 350 students in the primary level, 150 students in the upper primary level, and 97 students in the secondary level, 35 teachers and 15 non-teaching staff attending it on a normal working day. During the vacation periods from mid-December to mid-February and a week-long vacation in last week of June, only the 15 non-teaching staff were available at the school from 8:30 am to 2:30 pm. The students in primary and upper-primary level avail the PM Poshan scheme. As per survey, the amount of rice, pulses and vegetables cooked everyday were 55-60 kgs, 10-12 kgs and 25-30 kgs respectively well in norms with PM POSHAN Scheme (202).

Table 7.2 Building Rooftop Area Specifications

Building type	Type of Roof	Length (m)	Breadth (m)	Effective Breadth (m) for roof tilt	Number of panels	Effective Roof utilization by panels (%)	Area
Building 1	Flat	21.7	7.57	7.57	39	41.74	
Building 2	Flat	19.53	6.58	6.58	36	49.25	
Building 3	Tilted	25	9.03	9.96	96	74.79	
Building 4	(Assumed 30°) Tilted (30°)	10.5	8.0	8.82	40	83.79	

7.2.3 Load Data Generation

RAMP was used to generate the load profile. The appliances were visually inspected for their count and the written power ratings of the appliances have been identified. In situations where power ratings are not available, equivalent specification ratings have been collected from e-commerce websites (213). The variations in their usage time were considered based on the responses of the interviewees. Due to the repetitive schedule in the school, the percentage variations in the appliance usage were limited to 10-15 % for most appliances with slightly higher variations assumed for cell phone charging. Based on the input data, the different load profiles have been generated and are discussed in detail in the sub-sections below.

Table 7.3 Original Electrical Appliances

Appliance Name	Frequency of Use	P_{rated} (Watt)	Quantity	t_{max}	t_{min}	t_{maxvar}	N_{wind}	$t_{start,wind}$	$t_{end,wind}$	$t_{wind,var}$
Fluorescent Tube	Occasional	40	60	120	120	10%	1	8:40 AM	2:40 PM	10%
LED Bulb	Occasional	9	30	120	120	10%	1	8:40 AM	2:40 PM	10%
Ceiling Fan	Regular	60	50	300	300	10%	1	8:40 AM	2:40 PM	10%
Phone Charger	Occasional	25	35	90	20	20%	2	8:40 AM (W1) 12:30 PM (W1)	12:30 PM (W1) 2:40 PM (W2)	20%
Refrigerator	Regular	215	1	380	380	15%	1	8:30 AM	2:50 PM	10%
Bathroom Bulb	Occasional	5	15	60	5	15%	1	8:40 AM	2:40 PM	10%
Water Pump	Regular	750	1	60	30	10%	2	9:00 AM (W1) 2:00 PM (W1)	10:00AM (W1) 3:00 PM (W2)	10%
CCTV	Regular	4	4	360	360	10%	1	8:40 AM	2:40 PM	10%
Stand fan	Regular	60	2	120	60	10%	2	8:40 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	10%
Office PC	Occasional	240	1	240	90	10%	2	8:40 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	10%
Students PC	Occasional	360	10	80	40	10%	2	8:40 AM (W1) 1:20 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	10%
Printer 1	Occasional	650	1	30	5	10%	2	8:40 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	20%
Printer 2	Occasional	100	1	30	5	10%	2	8:40 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	20%
Printer 3	Occasional	465	2	30	5	10%	2	8:40 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	20%
TV 1	Occasional	75	1	120	60	10%	2	8:40 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	10%
TV 2	Regular	100	1	480	480	10%	1	8:40 AM	2:40 PM	10%
Router	Regular	20	1	360	360	10%	1	8:40 AM	2:40 PM	10%
Stereo	Regular	300	3	30	30	10%	2	8:30 AM (W1) 2:40 PM (W1)	8:40 AM (W1) 2:50 PM (W2)	5%
Laptop Charger	Occasional	75	5	180	60	10%	2	8:20 AM (W1) 12:50 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	20%
School Bell	Regular	10	1	15	5	10%	1	8:30 AM	2:50 PM	5%
Projector	Occasional	600	2	160	40	10%	2	8:40 AM (W1) 1:20 PM (W1)	12:50 PM (W1) 2:40 PM (W2)	10%
Photocopier Machine	Occasional	1386	1	30	10	10%	1	8:40 AM	2:40 PM	10%
Electric Cooking Range	Regular	8000	1	25	15	10%	2	10:00 AM 11:00 AM	11:00 AM 12:00 PM	15%

Table 7.4 Original Electrical Appliances during Holidays

Appliance Name	Frequency of Use	P_{rated} (Watt)	Quantity	t_{max}	t_{min}	t_{maxvar}	N_{wind}	$t_{start,wind}$	$t_{end,wind}$	$t_{wind,var}$
Fluorescent Tube	Occasional	40	60	120	120	10%	1	8:30 AM	2:30 PM	10%
Phone Charger	Occasional	25	60	90	20	20%	2	8:30 AM (W1) 12:30 PM (W2)	12:30 PM (W1) 2:30 PM (W2)	20%
Refrigerator	Regular	215	1	360	360	15%	1	8:30 AM	2:30 PM	10%
Water Pump	Regular	750	1	60	30	10%	2	9:00 AM (W1) 1:00 PM (W1)	10:00AM (W1) 2:00 PM (W2)	10%
Ceiling Fan	Regular	5	50	300	300	10%	1	8:30 AM	2:30 PM	10%

Table 7.5 Energy Efficient Electrical Appliances replacing appliances in Table 3.2 and 3.3

Appliance Name	Frequency of Use	P_{rated} (Watt)	Quantity	t_{max}	t_{min}	t_{maxvar}	N_{wind}	$t_{start,wind}$	$t_{end,wind}$	$t_{wind,var}$
LED Refrigerator	Occasional	9	5	120	120	10%	1	8:30 AM	2:30 PM	10%
	Regular	50	1	360	360	15%	1	8:30 AM 1:00 PM (W1)	2:30 PM 2:00 PM (W2)	10%
Ceiling Fan	Regular	35	50	300	300	10%	1	8:30 AM	2:30 PM	10%

7.2.3.1 Existing Electric Demand

The year were divided into four categories: i) Normal functioning of school during summer season (April to October) consisted of 126 days, ii) Normal functioning of school during winter season (February to March and November to the first week of December) consisted of 80 days, (iii) Summer vacation (last week of June) consisted of 6 days and iv) Winter Vacation (second week of December to January)) consisted of 35 days. Further, government holidays, second and fourth Saturdays of each month, along with Sundays, consisted of 118 days and did not require any demand for the entire day. The lists of appliances used during the normal school days and holidays are presented in Table 7.1 and Table 7.2 respectively.

7.2.3.2 E-Cooking Demand

The time taken for cooking the mid-day meal using LPG cylinder in the college was collected during the survey, and the corresponding specification requirements for electric appliances and time taken for e-cooking was estimated based on information gathered through interactions with different vendors of bulk e-cooking through (253) complemented by the information obtained from (241–243) after which the cooking load profile was generated using RAMP (Table 7.2).

7.2.3.3 Energy-Efficient Demand

Frequently used existing appliances were replaced by Energy-efficient appliances (196,254) to observe the changes in load demand and the outcomes of the techno-economic analysis compared to the existing load (Table 7.3).

Thus, a total of 4 load demand profiles were generated: i) Existing Load Demand (Load Profile 3) ii) Load profile employing e-cooking (Load Profile 1) iii) Load Profile employing energy-efficient appliances (Load Profile 4) and iv) Load Demand employing e-cooking and energy-efficient counterparts (Load Profile 2). Load Profile 1 was considered for the main investigation with the remaining profiles for sensitivity analysis.

7.2.4 Performance Ratio Modelling Using PVsyst

The PV panel power output depended on various factors such as temperature, solar irradiation, tilt angle, azimuth angle and PV performance ratio or derating factor (281,313). PVsyst offers 3 options for calculating number of panels or panel capacity in system pre-sizing user-interface, which are (283):

7.2.4.1 Based on required power

This method is generally used when the total capacity or power of the PV system to be installed is already known or planned before or assumed based on the demand. On specifying the capacity of a single panel, it divides the total capacity of the PV system by the rated capacity of a single panel to deduce the number of panels.

Its limitation is that space/spatial feasibility investigation is not possible as it is already assumed that there is sufficient area available for installation of the panels/ system. Further the losses are higher if optimum tilt and azimuth are not specified (as it considers a default value of 20° fixed tilt and 0° azimuth).

7.2.4.2 Based on available area

In this method, the area available for installation in provided as input. Then PVsyst considers a default value of 20° fixed tilt and 0° azimuth and deduces the approximate number of panels that can be

fitted based on the available area. Its limitation is that the total number of panels that can be installed are mostly overestimated as the shadows, obstructions, full panel positioning and regulatory restrictions are not considered and the entire area is considered for installation. Further the losses are higher if optimum tilt and azimuth are not specified. By this method, the total number of panels was deduced to be 325 panels of (315 kW) to be or 102.375 kW which is significantly higher than the actual deduced value in the present case-study. The break-up is provided below in **Table 7.6**.

Building	Number of Panels
Building 1	84
Building 2	66
Building 3	128
Building 4	47
Total	325

Table 7.6 Details of panel distribution over buildings based on available area

7.2.4.3 No sizing/ 3-D modelling/ Shadow modelling

This method is the manual option. This method was used for calculation of number of solar panels in the present-case study as it is the most realistic approach in the context of practical installation.

In this method, the optimum tilt and azimuth are generated using the in-built Transposition Factor tool available in PVsyst based on the longitude and latitude details of the location (for the flat roof buildings). “The Transposition Factor is the ratio of the incident irradiation on the plane, to the horizontal irradiation, that is, the fraction of radiation gained out of the horizontal radiation when tilting the collector plane.” At the optimum tilt and azimuth, the losses are minimum and the transposition factor is highest. The panels are placed manually on the building rooftops in a 3-D diagram generated using the near shading option in PVsyst at the optimum tilt and azimuth values with a random pitch value and approximate number of panels are generated at the beginning which may be slightly higher or lower than the actual value. This process may require multiple attempts of trial and error and also is dependent on the skill of the designer. After this arrangement, the optimum pitch is deduced using the in-built optimizer tool (available at PVsyst). At optimum pitch, the approximate number of panels considered generate the highest power/ energy over a period of time. After deduction of the optimum pitch value, the panels are readjusted/ repositioned as per the optimum pitch on the flat roofs and additional gap generated is used for filling up more panels or sometime panels have to be removed from the assumed value if gap is not available as per pitch. In this case-study, initially 36 panels and 6 m pitch are assumed on Building 1 in the optimizer simulator after which the optimum pitch was deduced to be 5 m. After re-positioning of the panels as per optimum pitch, additional gap was generated where 3 more additional could be fitted thus resulting in 39 panels on Building 1.

The same method can also be used for tilted roofs. However, in the present case-study, the optimum tilt and azimuth values were ignored for the tilted roofs and the panels were placed as per the roof tilt to place more panels on the roof top. However, the regulatory restrictions like minimum gaps at the roof edges (18 cm) at the bottom and at the top intersection and sideways were considered during the design which resulted in lesser number of panels than the designated area.

This method also provides flexibility with respect to rules and regulations of the building authorities and helps to provide gaps for walking and obstructions on flat and tilted rooftops and identify the scenario that despite sufficient area availability, panels may not fit simply due to shape misalignment of panels with the available area. Further analysis of impacts of shadows of far and nearby objects can also be considered (which impacts the performance ratio). In the present case-study the far shadow or horizon aspect has been considered (**Figure 7.3**)

The limitation of this method is the skill level of the designer who may be able to put in more panels with his/her expertise based on the proper positioning of the panels.

The PV panel power output depends on various factors such as temperature, solar irradiation, tilt angle, azimuth angle and PV performance ratio or derating factor (121,220). The optimum tilt angle, azimuth angle and pitch for maximum PV power output were calculated and the optimum PR was deduced using PVsyst based on specifications of components provided in **Table 7.7**. Based on these parameters and the roof top area of the school, a diagrammatic representation of the top view and the side view of the school was sketched in PVsyst and the maximum number of panels that can be placed

was estimated (**Figure 7.10** and **Figure 7.11**). The far shadow aspect (222) also has been considered for the location (**Figure 7.3**). The deduced PR value, and the maximum number of panels (as upper limit in search space of HOMER PRO) and the component specifications used by PVsyst were used in HOMER PRO for further analysis. The equations used for determination of PR of the solar panel via PVsyst (Equation 7.1- Equation 7.3).

The performance ratio/derating factor of the solar panel used was calculated using the following equation (220,222):

$$PR = \frac{Y_F}{Y_R} \quad (7.1)$$

Where

Y_F represents the “PV generator final energy yield”, which is calculated as follows:

$$Y_F = \frac{E}{P} \quad (7.2)$$

Where E is the Net Array Energy Output in kWh, P is the DC Power of Installed Array in kW.

Where Y_R is the reference yield of the PV generator

$$Y_R = \frac{G}{H} \quad (7.3)$$

Where G is the hourly radiation in W/m², H is the PV reference irradiance in hours.

The technical specification details of components used in PV Syst are provided in **Table 7.7**. For technical and economic modelling of components used in HOMER PRO are provided in Chapter 2 (Equation 2.1 to Equation 2.24).

7.2.5 Resource Assessment, Component Specification Details and Constraints

The average daily temperature and average solar irradiation data were estimated to be 12.94 °C and 4.79 kWh/m²/day (**Figure 3.4** and **Figure 3.5**). The technical and financial specification details of components along with constraints used in HOMER PRO were acquired from local manufacturers and distributors based on their availability in Indian market (**Table 7.4** and **Table 7.5**). The converters were assumed to be wall mounted and the Lead Acid batteries (LABs) were assumed to be kept in an unused storage room in the school of floor area 27.88 m², enough to place about 440 batteries of the present specification with sufficient spacing.

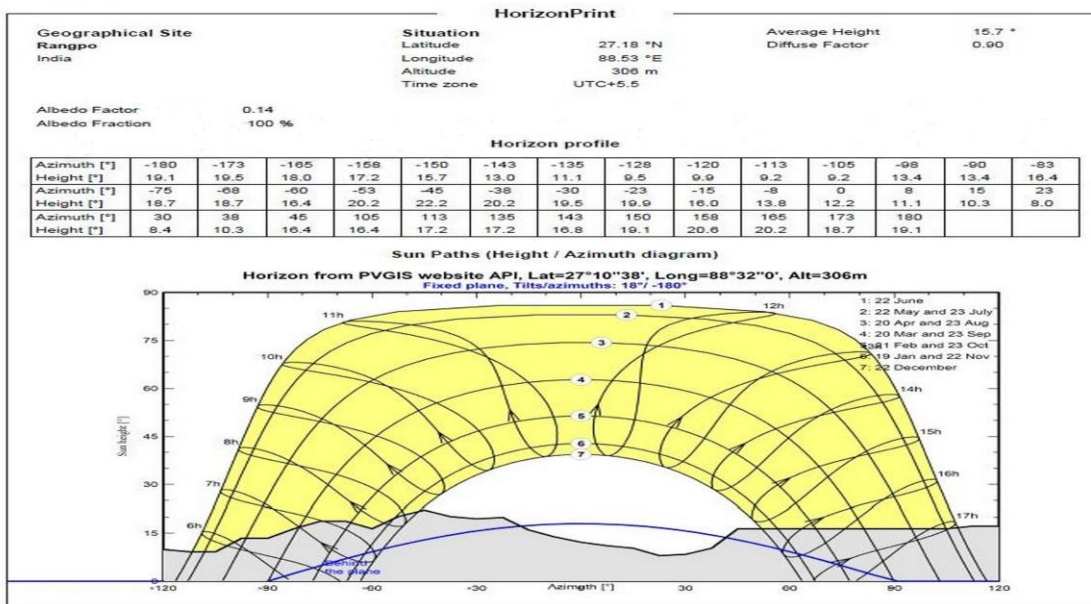


Figure 7.3 The horizon profile for the site location

7.2.6 Grid outage Modelling

The grid outages were also modelled for investigating the impact of grid unreliability on system performance (246). Based on survey, random outage was modelled with a mean outage frequency, average outage duration and duration variability of 150/year, 2 hours and 25% respectively and further planned outages were modelled from 9 am-11 am during summer season in HOMER PRO (Figure 7.4). The grid sales and purchase rates were provided in Table 7.7. Grid sellback rate was equal to 70% of grid purchase rate (255,256).

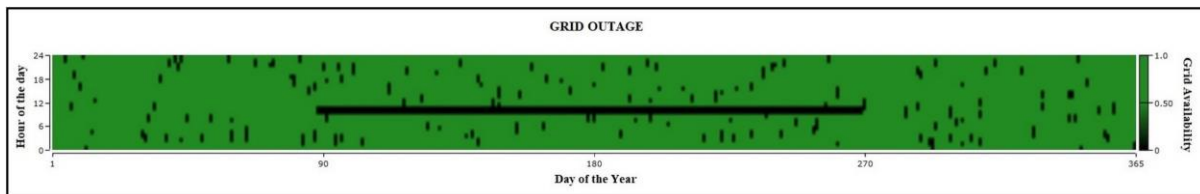


Figure 7.4 Grid Outage Modelling

Table 7.7 Technical and financial specifications of components for modelling in PVsyst and HOMER PRO

Component/ Issues	Parameter	Value	
PV System (195,261,262)	“Rated Capacity of each PV module” (E_{RPV})	315 W	
	Derating Factor(g_{PV})	65 %	
	Nominal Operating Cell Temperature($T_{c,NOCT}$)	44°C	
	Temperature Co-efficient(β_p)	-0.38 %/°C	
	Efficiency at Standard Conditions(η_c)	16.23 %	
	Lifetime	25 Years	
	Total Capital Cost of PV panel	457.143 \$/kW	
	Replacement Cost of Panel	457.143 \$/kW	
	Operation and Maintenance Cost	\$8/year	
	Tracking System	Maximum Power Point Tracking	
	Panel Base Area	1.94 m ²	
	Battery (195,262,263)	“Battery Type”	Lead Acid
		“Nominal Voltage”	12 V
“Nominal Capacity”		200 Ah	
“Rated Capacity”		2.4 kWh	
“Round Trip Efficiency”		85 %	
“Minimum Battery Life”		5 years	
	“Minimum State of Charge”	20%	

	“Capital Cost”	\$182.08/ battery
	“Operation and Maintenance Cost”	\$ 8/year
	“Replacement Cost”	\$144.58/battery
	“Battery Throughput”	2880 kWh @ 80% Depth of Discharge & 1500 cycles
	“Maximum State of Charge”	100%
	Battery C-Rating	C5
Converter (195,262,264)	“Converter Rated Capacity”	3 kW
	“Converter Efficiency”	98.3%
	“Lifetime”	15 years
	“Capital Cost”	\$116/kW
	“Operation and Maintenance Cost”	\$8/year
	“Replacement Cost”	\$116/kW
	“Converter Base Area”	0.076 m ²
	“Safety Factor/ Inverter Efficiency”	1.10
Grid (255,256)	Grid Purchase Rate	0.044 \$/kWh
	Grid Sellback Rate	0.0308 \$/kWh

Table 7.8 Constraints implemented in this analysis

Parameters	Value
“Interest Rate” (121,195)	8%
“Inflation Rate” (121,195)	4.7%
“Annual Capacity Shortage for standalone system” (121,195)	0%
“Project Lifetime” (121,195)	25 years
“Maximum Number of PV Panels”	144 (315W each)
“Maximum Number of Converters”	11 (3 kW each)
“Maximum Number of Batteries”	440 (2.4 kWh)

7.2.7 DSs

In HOMER PRO, several DSs can be formulated especially for grid-connected systems comprising of combinations of selective permissions or prohibitions on transactions among grid, other sources and the load. For this analysis, 5 DSs were formulated, comprising of 3 in-built HOMER PRO DSs and 2 customized DSs in MATLAB and implemented using HOMER-MATLAB interface which are elaborated below.

7.2.7.1 Standalone PV-Battery Configurations

This configuration consisted of PV and battery only and there was no involvement of grid. DS1 is the DS for this configuration. This is a HOMER in-built DS.

DS1

Both PV panels and batteries can meet the demand and PV panels can charge batteries. In this DS, the PV panels meet the demand first. If the demand is larger than the power generated by the PV panels, the remaining demand is met by the batteries. If the power generated by the PV panels and the batteries is not enough to meet the total demand, then the remaining demand is considered as unmet load or capacity shortage. If the demand is less than the power generated by the PV panels, the excess PV power generated is used to charge the batteries. The excess PV power remaining after meeting the demand and charging the batteries remains unutilized and is considered as excess electricity.

7.2.7.2 PV-Grid Configuration

This configuration consists of PV and grid only. There is no involvement of battery for this configuration. For this configuration, grid transactions are prohibited during grid outages. The two DSs for this configuration are DS2 and DS3.

DS2

Both PV panels and grid can supply the demand load and excess electricity can be vended to the grid during normal hours. During normal operation of the grid, the PV panels meet the demand first. If the demand is larger than the power generated by the PV panels, the remaining demand is met by the

grid. If the demand is less than the power generated by the PV panels, the remaining PV power is sold to the grid. During grid outage, PV panels are islanded/cut-off only from the grid and can meet the demand. If the demand is larger than the power generated by the PV panels, it remains as unmet load and cannot be met by the grid. On the other hand, if the demand is less than the power generated by the PV panels, the excess PV power remains unutilized as excess electricity as it cannot be sold to the grid. (Figure 7.5). This HOMER in-built DS is still not in practise, due to the inability of even the most advanced converters to instantaneously isolate the PV panels from the grid without battery back-up for meeting solely the demand load during grid outage.

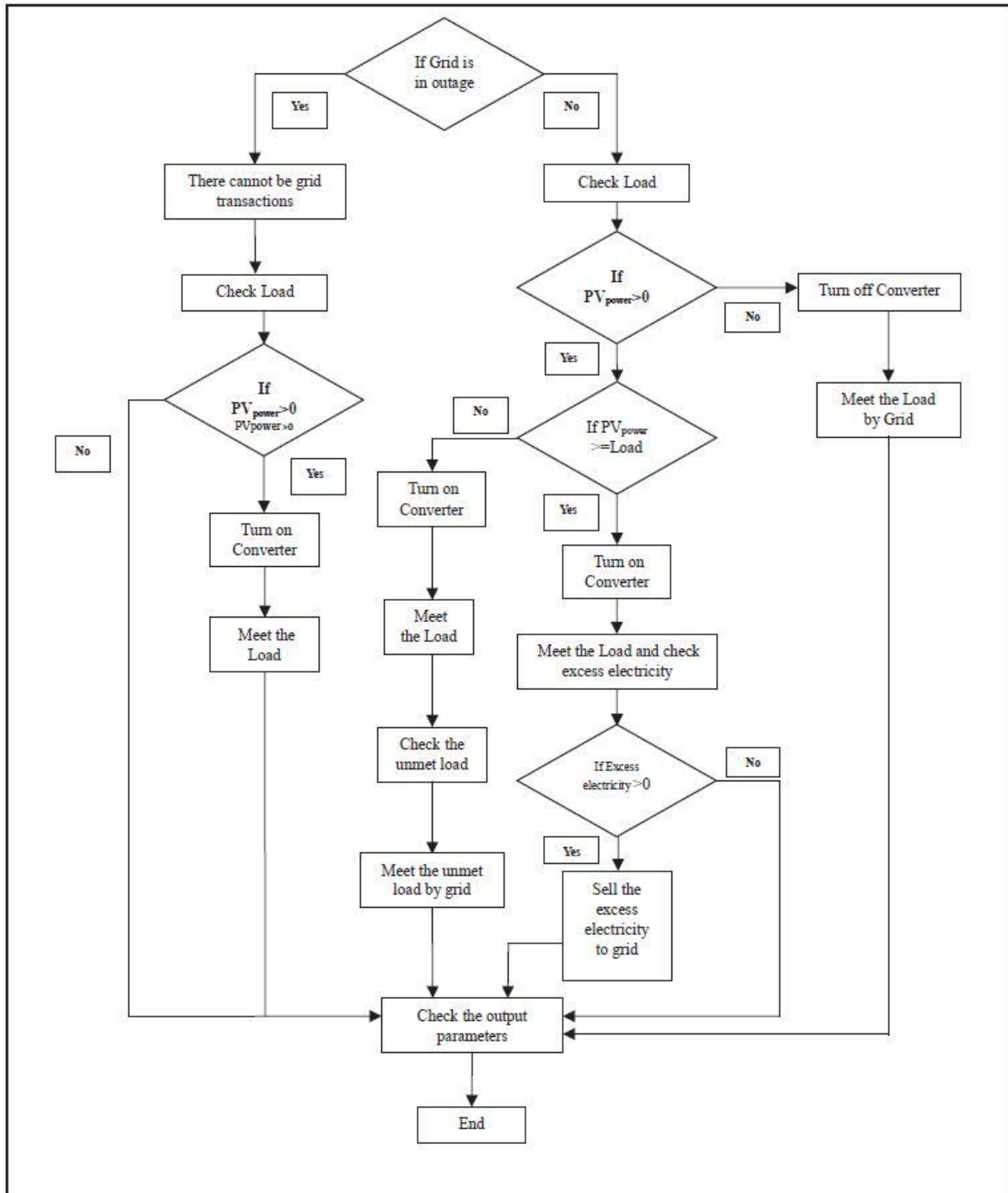


Figure 7.5 Dispatch Strategy 2

DS3 (HOMER-MATLAB link)

This DS was developed in MATLAB and interfaced with HOMER PRO using the HOMER PRO MATLAB link. It is same as DS2 during normal operation of the grid. During grid outages, neither PV panels nor the grid can meet the demand. Thus, the entire demand remains as unmet load during outages. The excess PV power cannot be sold to the grid and remains as excess electricity (**Figure 7.6**). This customized DS is still prevalent with traditional grid-tied converters without battery back-up.

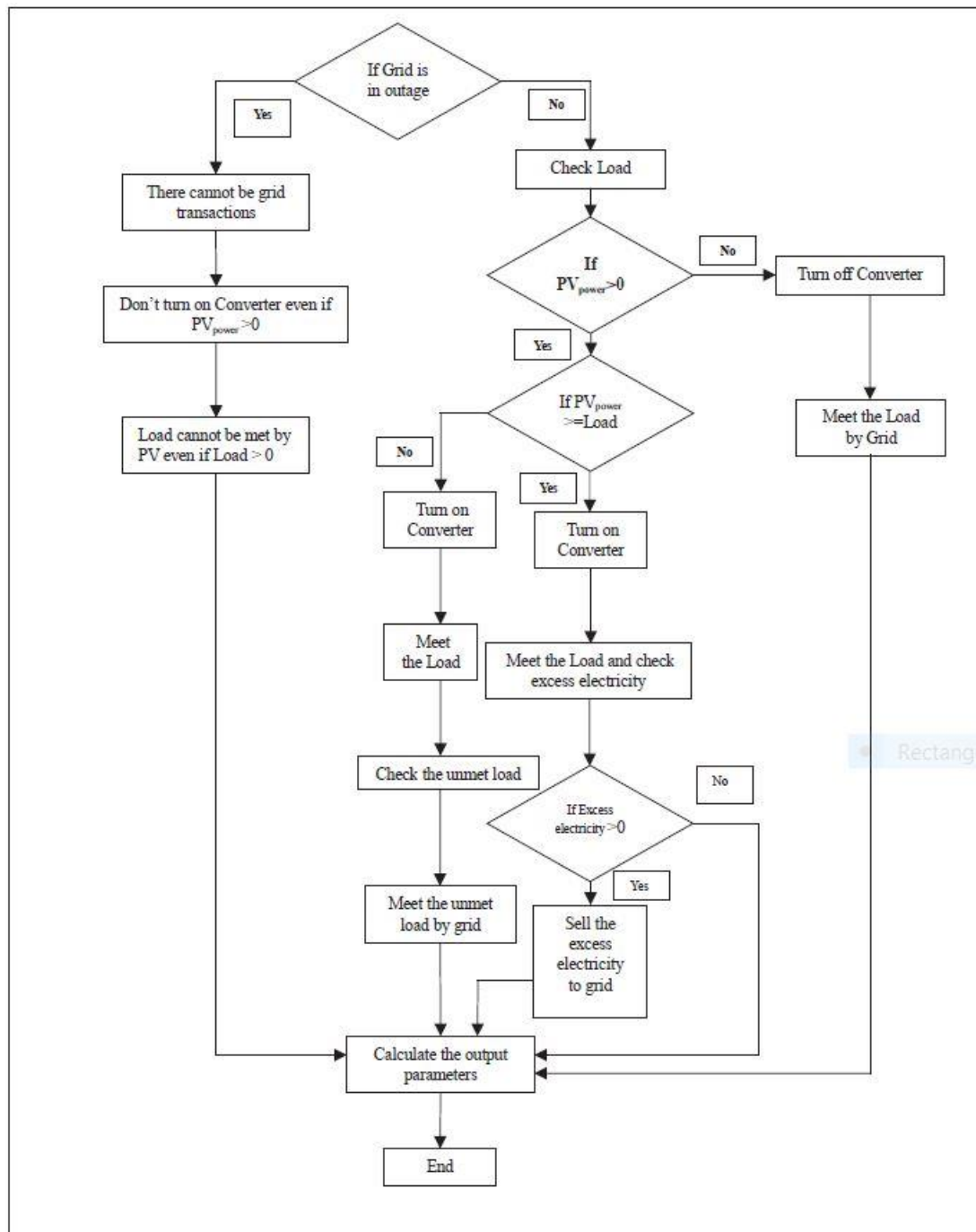


Figure 7.6 Dispatch Strategy 3

7.2.7.3 PV-Grid-Battery Configuration

This configuration consists of the PV, the grid and the battery. Like PV-grid, grid transactions are prohibited during grid outages. The two DSs for this configuration are DS4 and DS5.

DS4

Both PV panels and grid can supply the demand load and can charge the batteries when the grid is in operation. During normal operation of the grid, the PV panels meet the demand first. If the demand is larger than the power generated by the PV panels, the remaining demand is met by the grid. If the demand is less than the power generated by the PV panels, the remaining PV power is used to charge the batteries. If the batteries are not fully charged by PV panels, then the grid charges the battery till its full. On the other hand, if excess PV power remains after charging the battery, then it is sold to the grid. Excess electricity can be vended to the grid by PV panels only. Batteries cannot be discharged during normal operation of the grid.

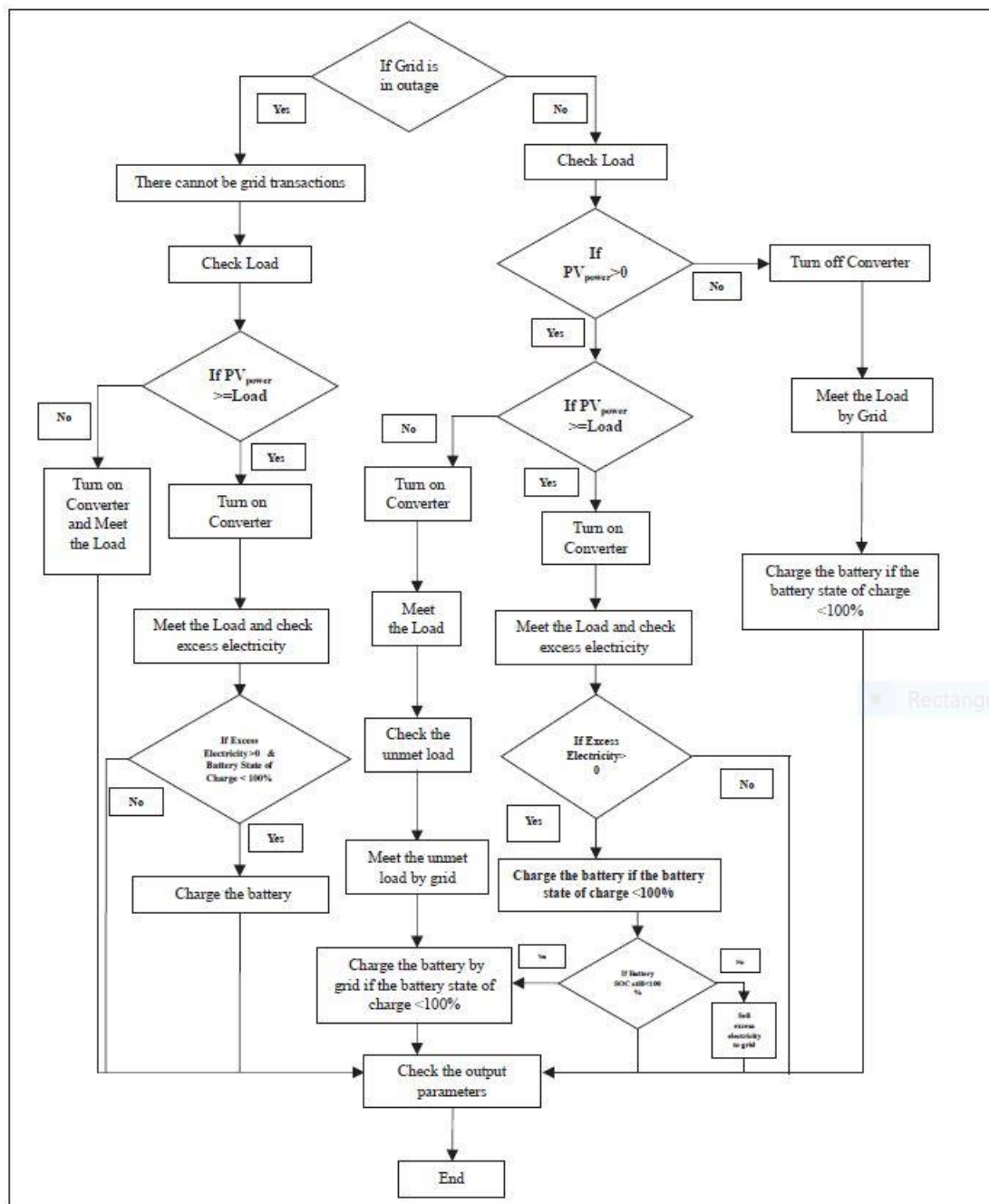


Figure 7.7 Dispatch Strategy 4

During grid outage, the PV-battery configuration isolates itself from the grid. Thus, both PV panels and battery can meet the demand even during outage. The PV panels meet the demand first. If the demand is larger than the power generated by the PV panels, the remaining demand is met by the

batteries provided the battery discharge power is higher than the remaining demand. If the power generated by the PV panels and the battery discharge power is not enough to meet the total demand, then the remaining demand is considered as unmet load or capacity shortage. If the demand is less than the power generated by the PV panels, the excess PV power generated is used to charge the batteries. The excess PV power remaining after meeting the demand and charging the battery remains unutilized as excess electricity and cannot be sold to the grid (**Figure 7.7**). This HOMER in-built DS has only recently been in practise, in mostly developed countries and is still in crude form due to technological limitations and requires advanced and expensive hybrid converters to perform this isolation instantaneously.

DS5 (HOMER-MATLAB link)

A DS developed in MATLAB; it is same as DS4 during normal hours.

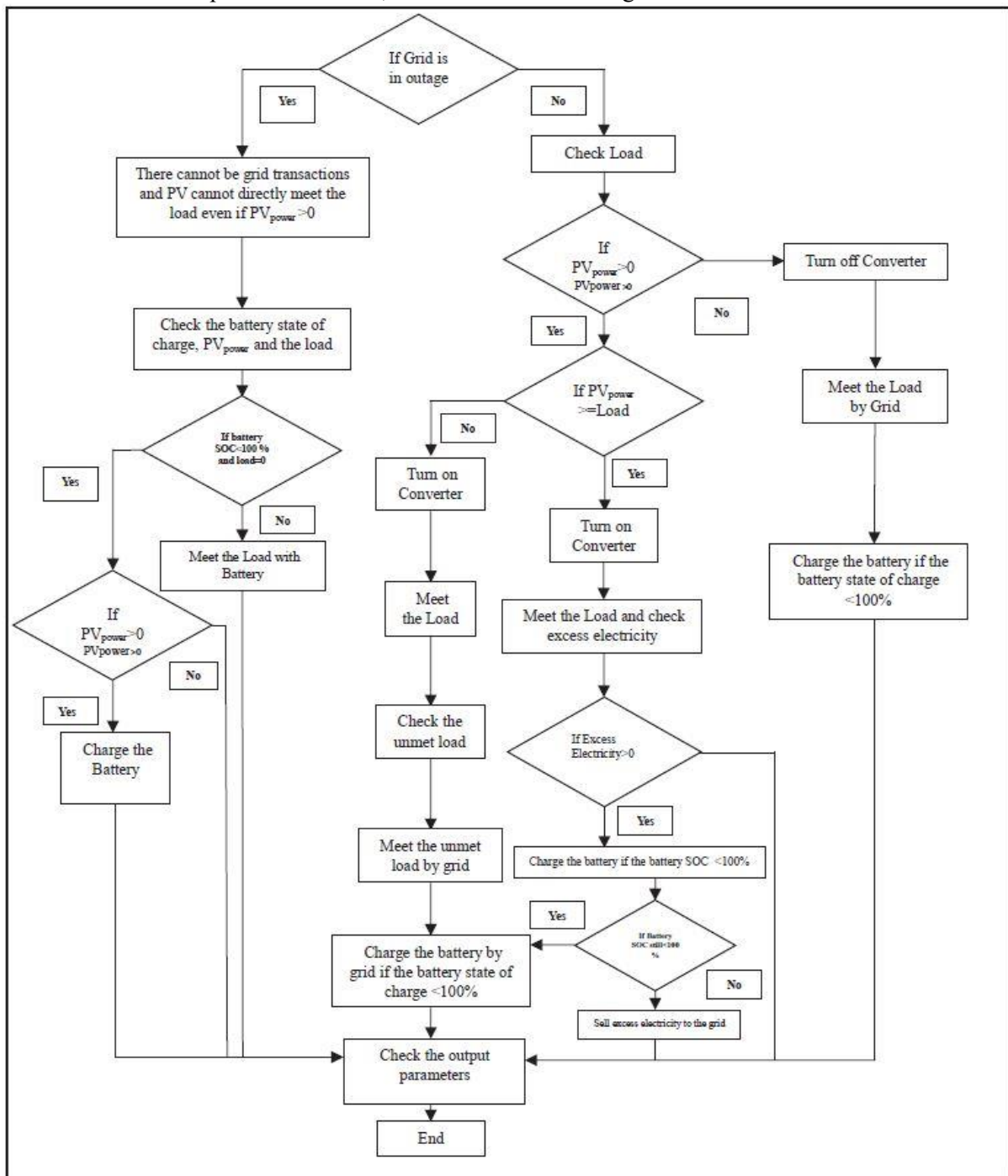


Figure 7.8 Dispatch Strategy 5

During grid outage, only batteries can meet the demand. The PV panels are cut-off from the load by the converter and also cannot meet the demand. PV panels can only charge the batteries when there is no demand and batteries are not fully charged. If the discharge rate of the battery assembly is higher than the demand then batteries can meet the demand and there is no unmet load. But if the discharge power of the battery assembly is lesser than the demand, then the entire demand remains as unmet load (**Figure 7.8**). This customized HOMER-MATLAB DS is employed by traditional hybrid converters and is widely prevalent in both developed and developing economies (276) till now due to the low cost of the converter (276).

7.2.8 Limitations of Methodology

The solar radiation used for investigation was based on a synthetic prediction software while the collection of primary data for appliance usage and modelling of grid outages was based on approximations of interview-based data and both can vary from real data. Further the same parameters for each battery and each panel were used during the whole project lifetime which may deviate the results from actual results as the conditions like battery degradation or panel degradation levels are non-uniform for every panel or battery and subsequent replacement times may vary from component to component in actual practise and are highly unlikely to take place at the same time. However, despite these limitations this investigation will be able to provide an approximate idea of the overall viability of the developed models. Further, sensitivity analysis was performed for several uncertain parameters to reduce bias in results.

7.3 Results and Discussion

7.3.1 Demand Load Generation by RAMP and HOMER PRO

The load profile details were presented in **Table 7.9** and **Figure 7.9**.

Load Profile 1 had the highest average and peak load at 11.62 kWh and 10.63 kW respectively, while Load Profile 4 had the least corresponding values at 6.73 kWh and 5.91 kW respectively. The percentage day-to-day variations were in the range of 86.41 %-94.41% with the highest variation for Load profile 4 and lowest for Load profile 3. The load factors were almost similar for all the load profiles ranging between 0.044 to 0.047. A low load factor for all the Profiles (**Table 7.9**) was due to a very low operation period of 8 hours and a large number of holidays for students (**Figure 7.9(e)-Figure 7.9 (f)**) which resulted in very low average demand. Due to absence of any security personal, every appliance was turned off during the closed period resulting in zero demand during that period.

Load profiles 1(**Figure 7.9(a), Figure 7.9 (e)**) and 2 (**Figure 7.9(b), Figure 7.9 (f)**) which employed e-cooking, showed a drastic increase in demand during the 10 am-12 am period than their respective counterparts without e-cooking, that is, Load profiles 3 (**Figure 7.9(c), Figure 7.9 (g)**) and 4 (**Figure 7.9(d), Figure 7.9 (h)**) , which was also indicated by the corresponding increase in peak and average loads (**Table 7.9**). Similarly, Load profiles 4 and 2 which employed energy-efficient appliances, had lower peak and average loads than their respective counterparts, that is, Load profile 3 and 1.

7.3.2 Results from PVsyst

The 3-D modelling done by PVsyst is provided in **Figure 7.10**. The optimum azimuth angle, tilt angle and pitch are 25°, -9° and 5 m respectively for the flat roof. The PV panels were placed according to the calculated parameters for the flat roofs, while for the tilted roof, the panels were placed to cover the entire roof (**Figure 7.11**).

The maximum number of PV panels (315 watts) that can be placed was 211 (**Figure 7.10** and **Figure 7.11**). The optimum PR is 65 %. The number of panels on the top of each building and the effective roof area utilization has been detailed in **Table 7.2**.

Table 7.9. Details of the different load profiles generated

Load Profile	Average Daily Consumption (kWh)	Peak load	Load factor	Day-to-day variations (%)
1	11.62	10.63	0.045	86.41
2	10.72	9.43	0.047	90.47
3	9.2	8.66	0.044	84.69
4	6.73	5.91	0.047	94.41

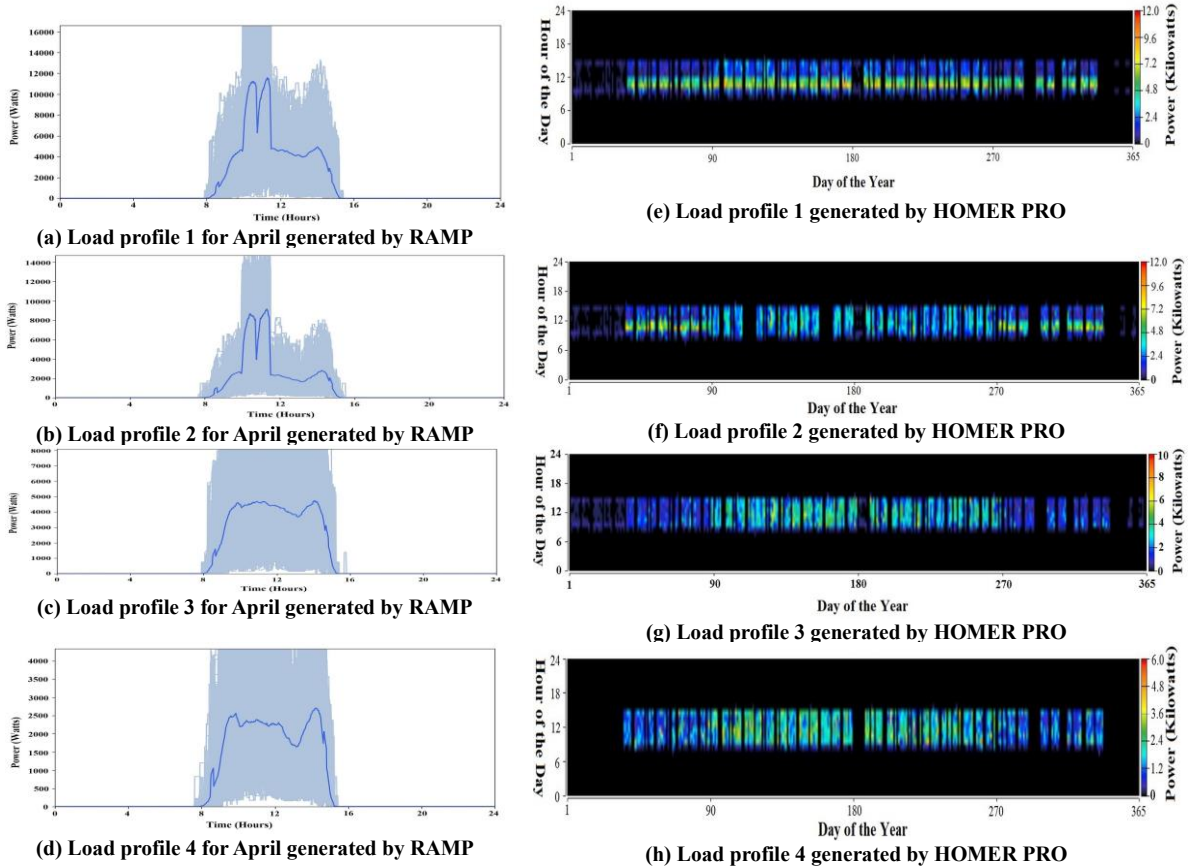


Figure 7.9. RAMP and HOMER PRO generated load profiles

For tilted roof buildings, the effective roof area utilization was less than 100% due to unavailability of complete area for installation of additional panels, and for maintaining rooftop panel regulations at the roof edges. The effective area utilization for both the flat buildings was less than 50 % due to several constraints like requirement of larger gaps in front of the rooftop entrance, structural constraints like water tanks, short poles on the rooftop, requirement of panel pitch area gap for optimum performance, minimum area requirements for accessing every corner of the roof by school authorities, and panel shape mismatch with the available area etc.

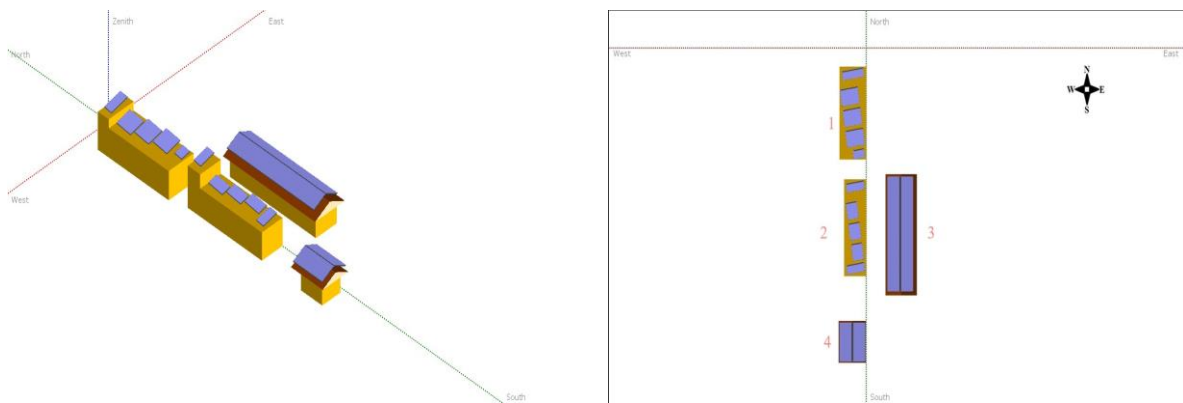


Figure 7.10 Diagrammatic representation of the school with solar panels in PV system

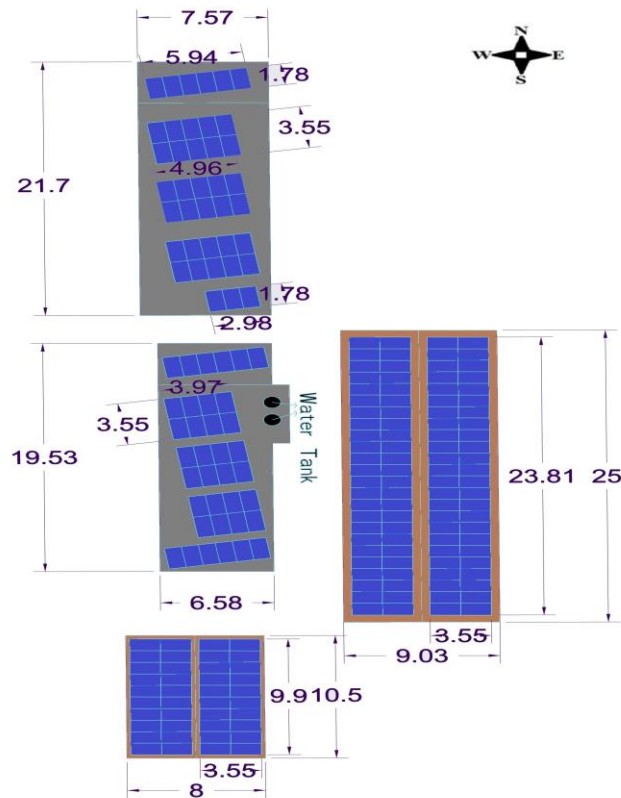


Figure 7.11. Rooftop layout with solar panels

7.3.3 Results generated by HOMER Pro

The maximum number of panels deduced by PVsyst was used as the upper limit of PV capacity for simulation in HOMER PRO. Further, the optimum tilt and azimuth angles and PR generated by PVsyst were also used for simulations in HOMER PRO. The detailed simulation results obtained for different DSs are presented in **Table 7.10**.

Table 7.10. Details of the results generated for the different DSs in HOMER PRO

Dispatch Strategy Number	System Configuration	PV array (kW)	Battery (kWh)	Converter (kW)	Number of PV Panels (0.315kW)	Number of Batteries (2.4 kWh)	Number of Converters	LCOE (\$/kWh)	Excess electricity (kWh/yr)	Excess Electricity (%)	Unmet Load (%)	Capacity Shortage (%)	Grid Purchase (kWh)	Grid sales (kWh)
1	Standalone PV-Battery	7.245	69.6	12	23	29	4 (3 kW)	0.228	2944	38.6	0	0	-	-
2	PV-Grid	66.465	-	33	211	0	11 (3 kW)	0.0348	6876	14.4	0.90	0.90	59.8	53160
3		66.465	-	33	211	0	11 (3 kW)	0.0363	8200	17.2	31.3	31.3	59.8	53160
4	PV-Grid-Battery	66.465	57.6	36	211	24	12 (3 kW)	0.0436	6583	13.8	0	0	72.8	53160
5		66.465	57.6	36	211	24	12 (3 kW)	0.0464	7612	15.9	0	0	72.8	52114

Among the three system configurations, for unreliable grid, the standalone PV-battery and PV-grid-battery configuration generated technically and spatially feasible solutions at 0% capacity shortage while the PV-grid configuration did not generate technically and spatially feasible solutions indicating the inability of such a configuration to provide reliable electricity for 24 hours of a day throughout the year when there is grid outage. The PV-grid configuration yielded result only at 0.90 % capacity shortage in DS2 (area infeasibility) and at 31.3 % capacity shortage in DS3 (technical infeasibility).

Among the feasible cases, the standalone PV-battery configuration had the highest LCOE at 0.228 \$/kWh in DS1. The PV-grid-battery configuration had an LCOE of 0.0436 \$/kWh in DS4 and 0.0464 \$/kWh in DS5.

7.3.4 Impact of different load profiles on LCOE

To understand the impact of changes in demand by using energy-efficient appliances and cooking appliances on LCOE, comparisons were made between all the load profiles without considering the additional capital costs incurred in purchase of new electric cooking range over conventional gas

range and purchase of energy efficient electric appliances over conventional appliances in the HOMER PRO simulation for DS1, DS4 and DS5 (**Figure 7.12**). For both DS4 and DS5, the LCOE decreased with decrease in average load demand as the excess electricity generated due to reduction in demand was sold to the grid and thus the least LCOE was observed for Load Profile 4 while the highest LCOE was observed for Load Profile 1 (**Figure 7.12(a)**). In case of DS1 involving standalone configuration without grid sales, the LCOE increased with increase in percentage day-to-day variations (**Table 7.9**) generated by random or uncoordinated use of appliances (67). Thus, Load Profile 4 had the highest LCOE while Load profile 3 had the least LCOE. The range of overall variations in LCOE among the different load profiles was very minimal (below 10%) in all the DSs when additional expenditure on appliances was not considered.

To understand the impact of additional expenditure by using energy-efficient appliances and cooking appliances on LCOE, comparisons were made between all the load profiles by considering the additional capital costs incurred in purchase of new electric cooking range over conventional gas range and energy efficient electric appliances over conventional appliances (**Table 7.3** and **Table 7.5**) in the HOMER PRO simulation for DS1, DS4 and DS5 (**Figure 7.12**). After this addition, significant increase in the LCOE were observed for Load profile 1, 2 and 4 over the Load Profile 3 (Existing Load Demand) in all the DSs with the highest increase being observed for Load profile 2 which included additional expenditure for introducing both cooking and energy efficient appliances (**Figure 7.12**). Consideration of additional expenditure on cooking appliances (Load Profile 1) increased the LCOE by about 18% over existing load demand (Load Profile 3) (**Figure 7.12(a)**) in DS5. Similarly, consideration of additional expenditure (Load Profile 4) on energy efficiency appliances increased the LCOE by about 50 % over existing demand (Load Profile 3) in DS5. Consideration of expenditure on both energy efficient appliances and cooking appliances (Load Profile 2) increased the LCOE by about 76% over Load Profile 3 in DS5. Almost similar trends are observed for DS4 (**Figure 7.12 (a)**) and DS1 (**Figure 7.12 (b)**).

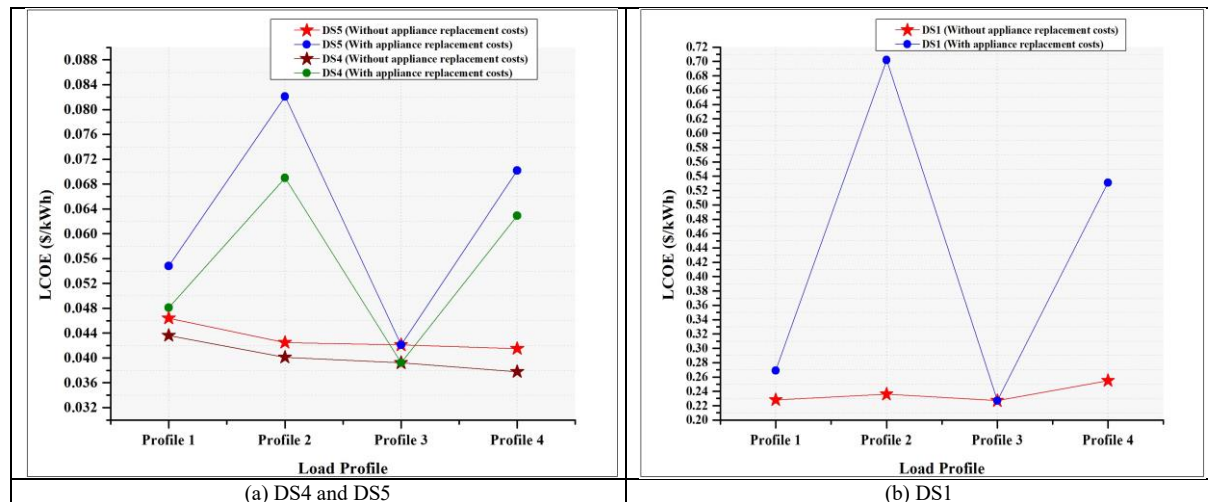


Figure 7.12. LCOEs for Various DSs after including additional capital costs for Cooking and Energy Efficient appliances

7.3.5 Economic feasibility analysis of technical and spatially feasible configurations

To comprehend the economic viability and competitiveness of the technically and spatially feasible configurations (the standalone configuration (DS1), PV-grid-battery configuration (DS4 and DS5) against the existing supply scenario of PV-DG-LPG in the school and another prevalent configuration of grid and battery (grid-battery configuration) in grid-outage ridden locations, a comparative analysis was conducted for LCOE among them for all the load profiles.

The economic and technical output parameters for the existing energy supply scenario (grid-DG-LPG configuration) in the school, where grid supplies the load demand and diesel generator supplies the load demand during outage and LPG cylinders are used to meet the cooking demand, were deduced using input data provided in **Table 7.7**. HOMER PRO was used to determine the LCOE for the electric demand while the LCOE for cooking was calculated using modified forms of Equation 2.21-

2.24. The output parameters are provided in **Table 7.15**. The LCOE for the existing scenario was 0.306 \$/kWh. Further, LCOE of another common energy supply scenario (grid-battery configuration), prominent in outage-ridden locations where batteries are used to meet the demand when the grid is in outage, was deduced with HOMER PRO to be 0.212 \$/kWh.

Table 7.11 Global Warming Potential of different components

Components	Life Cycle emissions
Solar PV system (110)	0.05 kgCO ₂ eq / kWh
DG system(110)	2.68 kgCO ₂ eq /kWh
Grid Purchase (110–112)	0.8 kgCO ₂ eq /kWh
LPG (113)	0.564 kgCO ₂ eq /kWh
Battery (97,100)	0.3 kgCO ₂ eq /kWh
Grid sales from PV (110)	-0.75 kgCO ₂ eq /kWh
E-cooking Appliance (Induction stove) (114)	1300 kgCO ₂ eq /stove
Gas cooking appliance (Gas stove) (114)	652 kgCO ₂ eq /stove

Table 7.12 Expenditure Details of Existing and Energy efficient appliances for electric end-use

Existing Equipment (Unrated)						
Equipment	Life time	Cost per quantity (\$)	Inflation Rate	Quantity	Number of replacements during project life	Total Capital Cost (\$)
Fan	2 (86)	11.43 (86)	6%	60	13	19693.91
Fluorescent Tube	1 (86)	3.11 (86)	6%	60	26	11038.58
Refrigerator	10 (86)	120.18 (86)	6%	1	2	720.87
Total Lifetime Capital Costs						31453.36
Replacing Equipment (Energy Efficient)						
Fan	5 (86)	70.27 (86)	6%	60	5	41035.29
LED Bulb	1 (86)	1.7 (86)	6%	60	26	6033.95
Refrigerator	10 (86)	266.69 (86)	6%	1	2	1599.60
Total Lifetime Capital Costs						48668.84
Total Capital Costs Incurred						17215.48

Table 7.13 Expenditure Details of Appliances for cooking end-use

Existing Equipment (Gas)						
Equipment	Life time	Cost per quantity (\$)	Inflation Rate	Quantity	Number of replacements during project life	Total Capital Cost (\$)
Commercial Gas Range	10 (86)	120 (86)	6%	2	2	1439.51
Replacing Equipment (Electric)						
Commercial Induction Cooktop	10 (86)	720 (86)	6%	1	2	4318.72
Total Capital Costs Incurred during Project Lifetime						2879.205

Table 7.14 Project Lifetime Energy Output of Different Configurations

Configuration	Lifetime output (kWh)					
	PV Output	Battery Output	Grid Purchase	Grid Sales	LPG Output	DG output
Standalone PV-Battery (DS1)	190425	43250	0	0	0	0
PV-Grid-Battery (DS4)	1746950	987.5	927.5	1337775	0	0
PV-Grid-Battery (DS5)	1746950	34700	927.5	1302950	0	0
Grid-Battery	0	34700	72775	0	0	0
Grid-DG-LPG	0	0	72775	0	77343	10700

Despite the increase in LCOE in PV-grid-battery configuration (DS5) with the use of e-cooking appliances and energy-efficient appliances (**Figure 7.12(a)**), the LCOE values for Load Profile 1(0.0548 \$/kWh) and Load Profile 2 (0.0821 \$/kWh) and Load Profile 4 (0.0702\$/kWh) were still considerably lesser than the LCOE for the existing supply configuration of grid-DG-LPG (0.306 \$/kWh) and the alternate prevalent battery-grid configuration (0.212 \$/kWh).

The LCOE after consideration of cooking appliance expenditure in DS1 at 0.269 \$/kWh (Load Profile 1) for standalone PV-battery was also lesser than the existing supply configuration and only

slightly higher than the alternate prevalent configuration. However, the additional expenses on energy-efficient appliances (Load profile 2 and 4) significantly increased the LCOE for the standalone configuration.

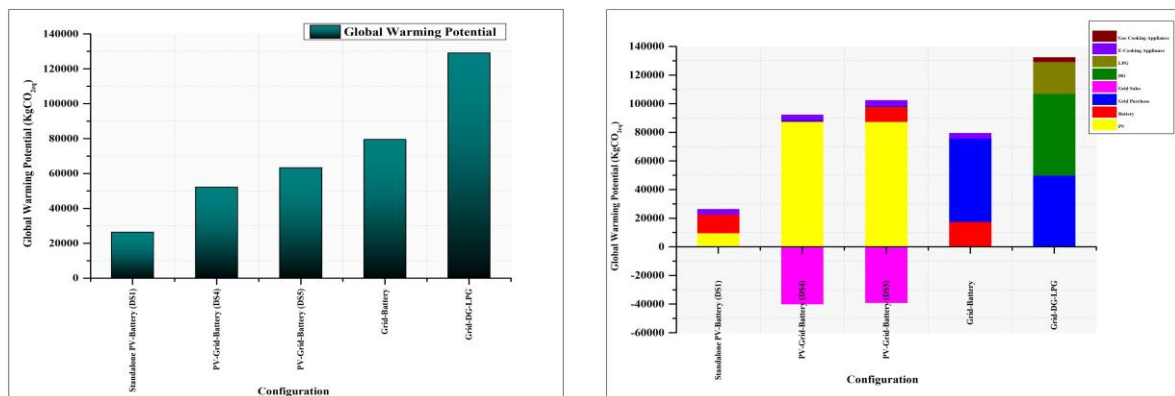
Table 7.15. The economic output parameters for existing scenario

Electric Demand	
Total Annualized Costs	\$ 855.13
Total Electrical Load Served	3339 kWh/year
LCOE (Electric)	0.256 \$/kWh
Cooking Demand	
Total Annualized Costs	\$ 1113.83
Total Cooking Load Served	3094.83 kWh
LCOE (Cooking)	0.36 \$/kWh
Net (Electric and Cooking) Demand	
Total Annualized Costs	\$ 1968.96
Total Load Served	6433 kWh
LCOE (Net)	0.306 \$/kWh

Thus, the addition of e-cooking demand on existing demand was economically viable for both PV-grid-battery configuration and standalone PV-grid-battery configuration. Though the replacement of unrated appliances with energy efficient appliances was only economically feasible for PV-grid-battery configuration. Thus, both standalone PV-battery and PV-grid-battery were economically feasible with PV-grid-battery being the most economically attractive option.

7.3.6 Environmental viability analysis of the technically, economically and spatially feasible configurations

To comprehend the environmental viability of the technically, economically and spatially feasible configurations, a comparative analysis was conducted for the global warming potential (GWP) in kgCO_{2eq} among the standalone configuration (DS1), PV-grid-configuration (DS4 and DS5), grid-battery configuration and the existing supply scenario of grid-DG-LPG for Load Profile 1. The CO_{2eq} values of different components involved in this analysis has been provided in **Table 7.11** and the project lifetime energy output of different components have been provided in **Table 7.14**. Based on these parameters, the CO_{2eq} in kgs for the project lifetime were calculated for the four configurations (**Figure 7.13**). The modelled configurations (DS1, DS4 and DS5) had lesser GWP than more prevalent grid-battery and the existing scenario of grid-DG-LPG in the school (**Figure 7.13(a)**).



(a) Overall GWP of the 4 configurations (b) Component-wise breakup of GWP
Figure 7.13. Global Warming Potential of the configurations

The stand-alone configuration had the least GWP while the existing configuration (grid-DG-LPG) had the highest GWP. The existing configuration had the highest kgCO_{2eq} due to use of three fossil fuel-based systems namely grid, DG and LPG. Despite a high kgCO_{2eq} emission in PV-grid-battery configuration, the grid sales from a system (PV system) with lesser GWP to a system with higher GWP (grid) in DS4 and DS5 significantly reduced the GWP of the grid and consequently that of PV-grid-battery configuration (DS4 and DS5) (**Figure 7.13(b)**). Thus, both standalone PV-battery and PV-grid-battery were environmentally competitive with standalone PV-battery being the most environmentally attractive option.

7.4 Validation of Results

7.4.1 Validation of Load Data Generated by RAMP

Due to absence of smart meter in the school, the validation of high-resolution time-series data generation by RAMP with metered data was not possible. However, an approximate attempt was made by comparing the summed up monthly load data generated by RAMP with the monthly electricity bills of the school for the year. Sample monthly electricity bills for the months of June and July has been provided in **Figure 7.15** and **Figure 7.14** compares the RAMP generated monthly demand (Load Profile 3) with the monthly billed demand. The RAMP demand was higher than the billed demand for most of the months with prominent grid outages (April-September) as the demand supplied by DG during outages was not recorded in the monthly bills. July and August were notable exceptions where billed monthly demand was close to RAMP monthly demand despite frequent outages as the school authorities conducted occasional cultural events and after school hour and weekend practises for those events during these months which were not included for RAMP data. Maximum variation between the load profiles was observed in May at 30.25% while it was minimum at 1.18% in July. The range of variation was relatively lesser during the months with lesser grid outages (October-March) at 2.18 %-11.68% compared to the months with more grid outages (April-September) at 1.18-30.25%.

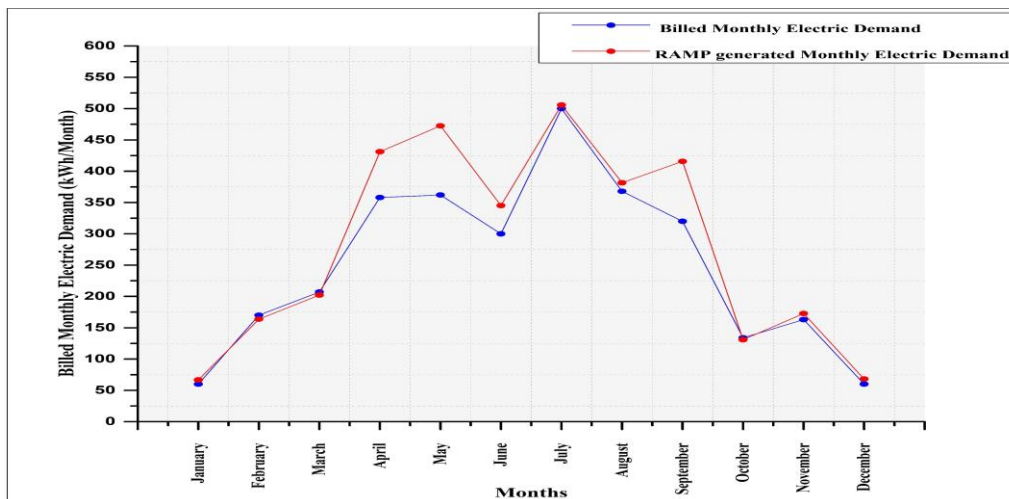


Figure 7.14. Comparison between monthly billed load profile and RAMP generated load profile (Load Profile 3)

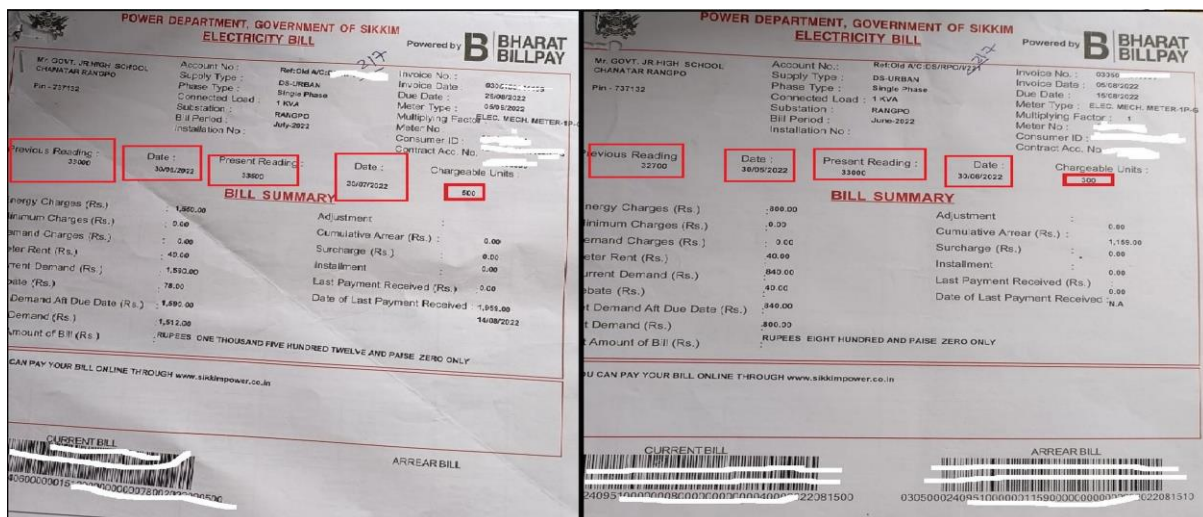


Figure 7.15 Sample Bills for the Month of June and July for the investigation period

7.4.2 Validation of DS3 and DS5 developed in MATLAB

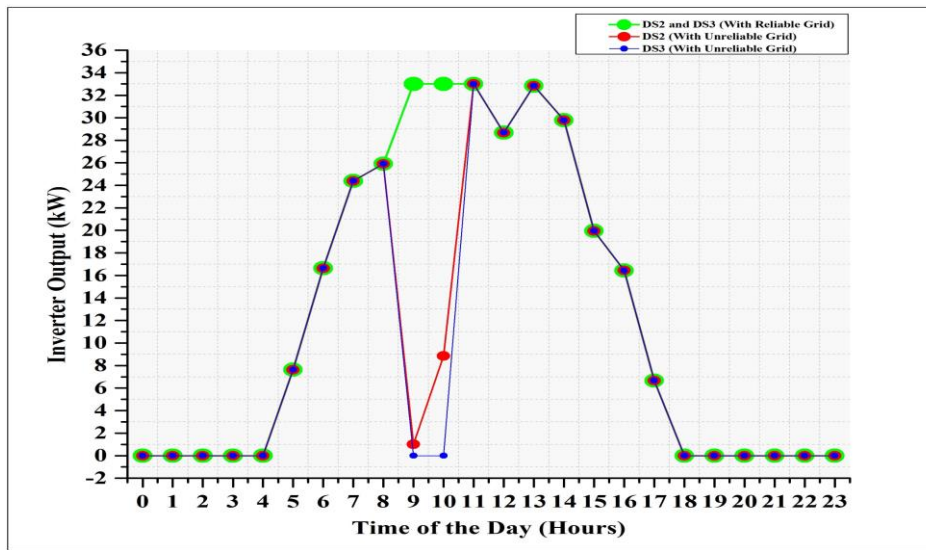
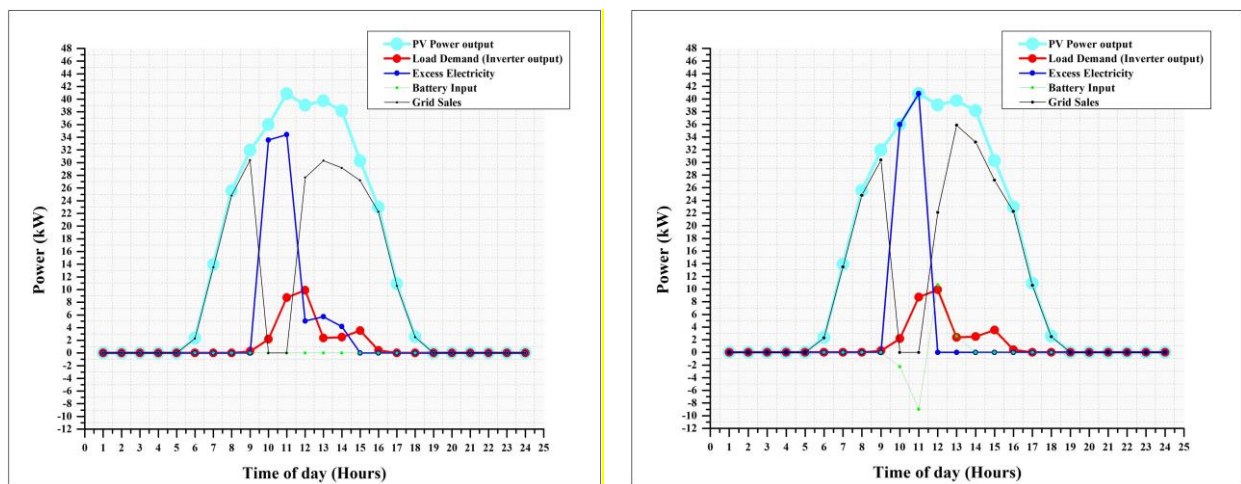


Figure 7.16. Comparison of DS2 and DS3 on a random day in April

DS3 and DS5 were validated on the basis of comparison of energy balance results between DS3 and DS2 and between DS5 and DS4 respectively, obtained from HOMER PRO in .csv file format for a random day in April especially during the outage hours (9:00am-11:00 am) during that day. For the entire day, PV power was larger than demand at every time step during the daytime.



(a) DS4

(b) DS5

Figure 7.17. Comparison of DS4 and DS5 on a random day in April

On comparing DS2 and DS3, the inverter output was same for every hour of the day for both DS2 and DS3 for reliable grid (Figure 7.16). However, for unreliable grid, during outage period (9:00am-11am), the inverter output was equal to the demand (Figure 7.16) in DS2 while it was 0 kW in DS3. For the remaining hours DS2 and DS3 had the same results. Thus, DS3 was validated.

On comparing DS4 and DS5 for unreliable grid, during the outage period (9:00am-11am) only battery discharged for DS5 equal to the demand (Figure 7.17(b)) and PV power was totally unused as indicated by the equivalent excess electricity unlike DS4 (Figure 7.17 (a)) where battery did not discharge and only PV met the demand as indicated by the reduced excess electricity. Unlike DS4, the battery was thereafter charged by PV between (11:00 am-12:00 pm) in DS5 (Figure 7.17 (b)) which resulted in reduced grid sales for DS5 than DS4. For the remaining hours, DS4 and DS5 had the same results. Thus, DS5 was validated.

7.4.3 Validation of simulation results of PVsyst and HOMER PRO with other literatures

The PR value of 0.65 obtained for this analysis via PVsyst was well within the range of 0.6-0.9 obtained in other literatures (229,250,276,279,291,293) though on a conservative side mainly due to the far shadow aspects of hills prevailing in the location (**Figure 7.3**).

Despite the same location and almost same economic and technical input parameters, substantial differences in LCOE for the standalone PV-battery configuration were observed among this study, (67) and (313) indicating the impact of load profile differences and PR on the LCOE. The LCOE (0.227 \$/kWh) deduced for the standalone configuration for Load profile 3 (Existing demand without e-cooking) in the present-study closely matched the LCOE (0.217 \$/kWh) for the standalone configuration for a similar load profile in a school in Roorkee (294) where the system was experimentally verified for self-sustainability. The minor difference may be governed by the climatic variations of the location as both the investigations have been conducted in almost similar period of time.

The LCOE of this study for DS4 (**Figure 7.25**) for Load Profile 1 (without considering costs of e-cooking appliances) for New Delhi (ND) closely matches the LCOE of 0.053 \$/kWh observed in (319), considering the fact that the present investigation and (319) were conducted in a similar period of time. However, no penalty on grid overfeeding was considered in the present-study unlike (319). If grid overfeeding penalty was considered for the present case, then the configuration in DS4 will have incurred more penalty than DS5, due to higher grid sales which might have further increased its LCOE.

7.5 Sensitivity Analysis

For further validation and comprehension of the results on broader foundations, sensitivity analysis for different uncertain parameters have been conducted and discussed in the following sections.

7.5.1 Comparison and significance of the PV-grid configuration DSs

To understand the significance of the impact of grid outages and grid sales on the configuration performance, sensitivity analysis was performed to analyse the impact of change in PV capacity on capacity shortage, grid sales and LCOE in the 2 DSs of PV-grid configuration (DS2 and DS3) for both reliable and unreliable grid (**Figure 7.18**).

At 0 % PV capacity, the source of power was only grid, while 100 % PV capacity was the maximum PV capacity of 66.465 kW used in this case study.

There was no capacity shortage (**Figure 7.18 (a)**) or unmet load for reliable grid. But for an unreliable grid, the capacity shortage was at 31.3 % with only grid (0 % PV capacity). With the increase in PV penetration, the capacity shortage reduced in DS2 as the PV panels met the demand during grid outages. However, the capacity shortage did not reduce in DS3 even with increase in PV penetration as the PV panels were cut-off from the demand during outages. Thus, the configuration became completely infeasible with unreliable grid in DS3 unlike DS2 where with further penetration (beyond 66.465 kW) feasibility could have been achieved. However, for the present case-study, DS2 could not totally eliminate the capacity shortage even at 100 % PV capacity, thus making the configuration infeasible and indicating the limitations of roof top area availability and the consequent shortage of PV capacity in the school.

The failure to meet the load demand during grid outage led to variations in primary load met in the 2 DSs (**Figure 7.18 (b)**). Despite the increase in PV penetration, the PV panels were unable to go beyond the primary load of 2911 kWh in DS3, as the remaining demand arose at the time of grid outage. However, the primary load met by PV-grid configuration in DS2 increased with the increase in PV penetration for unreliable grid; though the configuration was still unable to completely meet the total primary load of 4296 kWh at its full capacity. However, for a reliable grid the configuration could meet the primary load of 4296 kWh in both the DSs as any shortage in meeting the load demand by the PV panels was being compensated by the grid. Thus, the LCOE decreased with increase in primary load met/served at a particular total system cost, and consequently the LCOE was higher in DS3 than DS2

for unreliable grid at a particular PV capacity and further reduced in both DSs for a reliable grid (**Figure 7.18 (c)**).

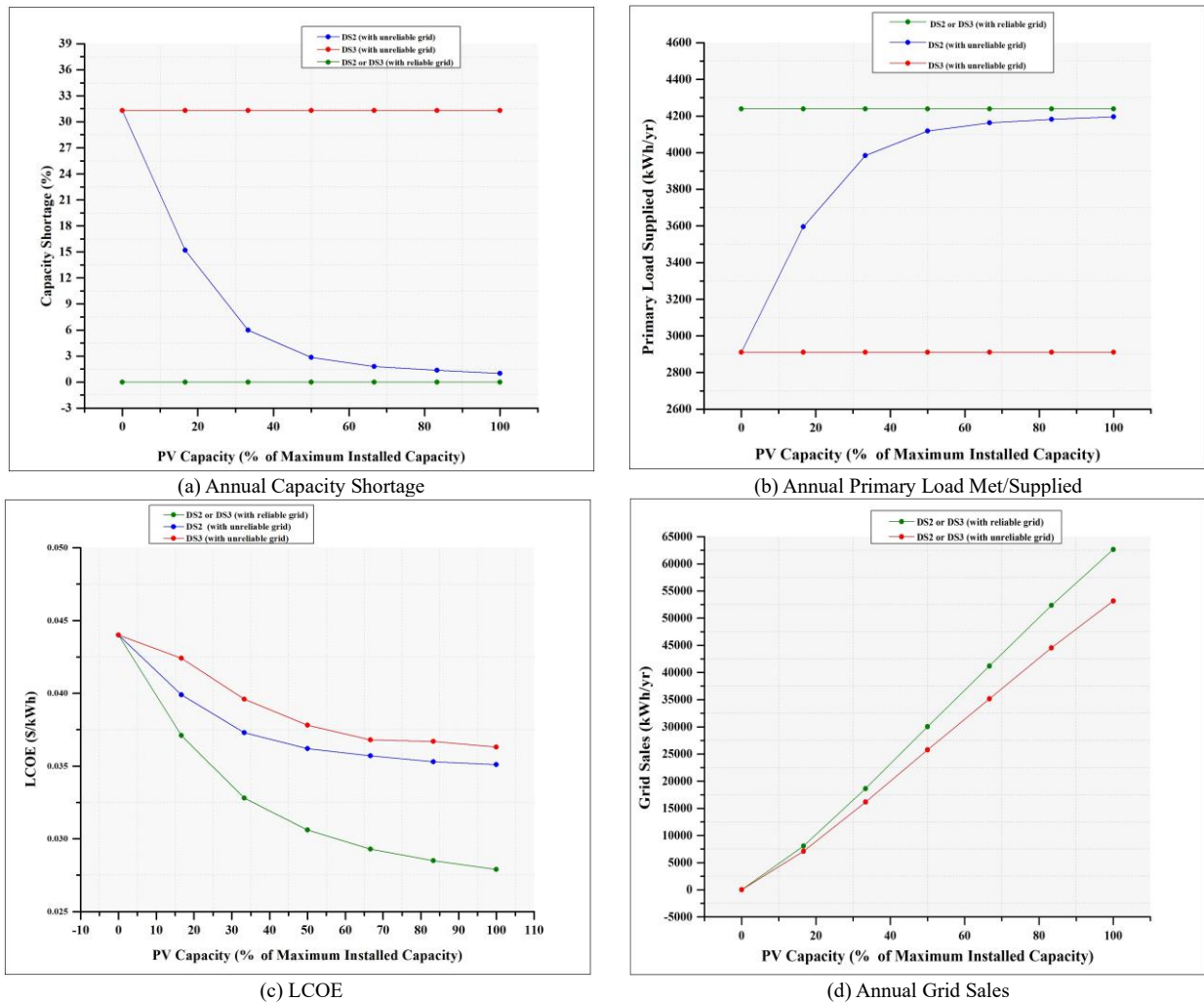


Figure 7.18. Comparison of DS for output parameters of PV-grid configuration for reliable and unreliable grid with change in PV capacity

The annual grid sales, at a particular PV capacity in DS2 and DS3 was lesser for unreliable grid than reliable grid (**Figure 7.18 (d)**) due to prohibition of grid sales during grid outages which resulted in a higher LCOE in both DS2 and DS3 for unreliable grid than reliable grid (**Figure 7.18 (c)**).

The grid sales increased with increase in PV capacity in DS2 and DS3 (**Figure 7.18 (d)**) which reduced the overall system costs and the LCOE (**Figure 7.18 (c)**).

Sensitivity analysis was also performed to understand the impact of change in PV capacity on output parameters like battery energy transactions, grid sales and LCOE of PV-grid-battery configuration in DS4 and DS5 for both reliable and unreliable grid (**Figure 7.19**).

Unlike PV-grid configuration, there was no capacity shortage in any DS for unreliable grid as the batteries supplied the remaining unmet load. Thus, capacity shortage plots were replaced by battery throughput plots where the battery input (**Figure 7.19 (c)**) and output plots (**Figure 7.19 (d)**) followed similar trends to **Figure 7.18(a)**. The battery throughput remained constant for DS5 but decreased for DS4 with increasing PV penetration. The battery throughput was zero in both DS4 and DS5 for reliable grid indicating no requirement of batteries. Similar to PV-grid configuration, the grid sales increased with increasing PV capacity which reduced the LCOE. The grid sales were highest in both DS4 and DS5 for reliable grid at a particular PV capacity. However, the grid sales for DS5 were lesser than DS4 for unreliable grid as during grid outages the batteries were discharged more for DS5 than DS4 during

outages (**Figure 7.17**), consequently during normal hours the PV panels after meeting the load utilize more electricity to charge the batteries in DS5 than DS4 thus resulting in lesser electricity available for

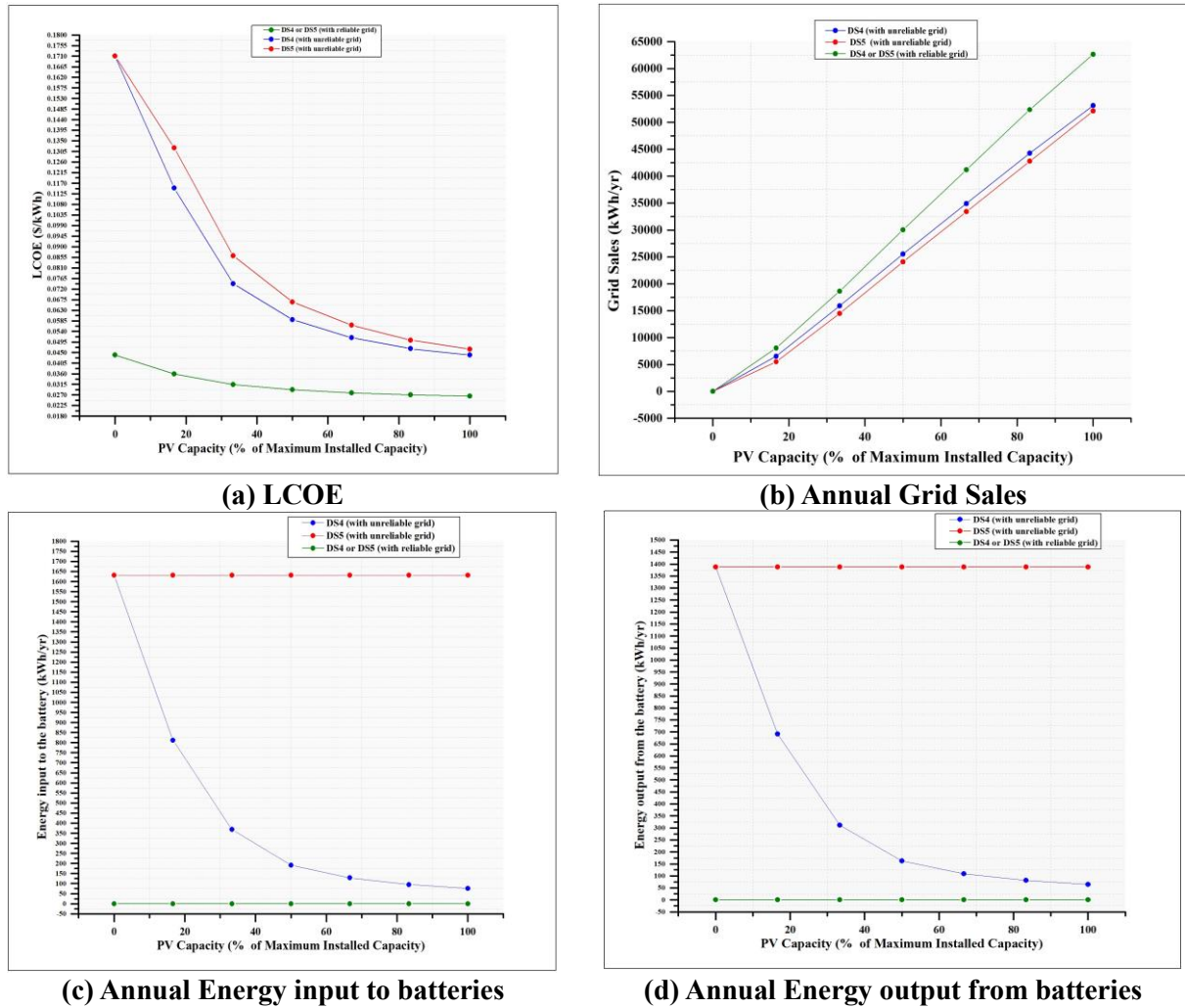
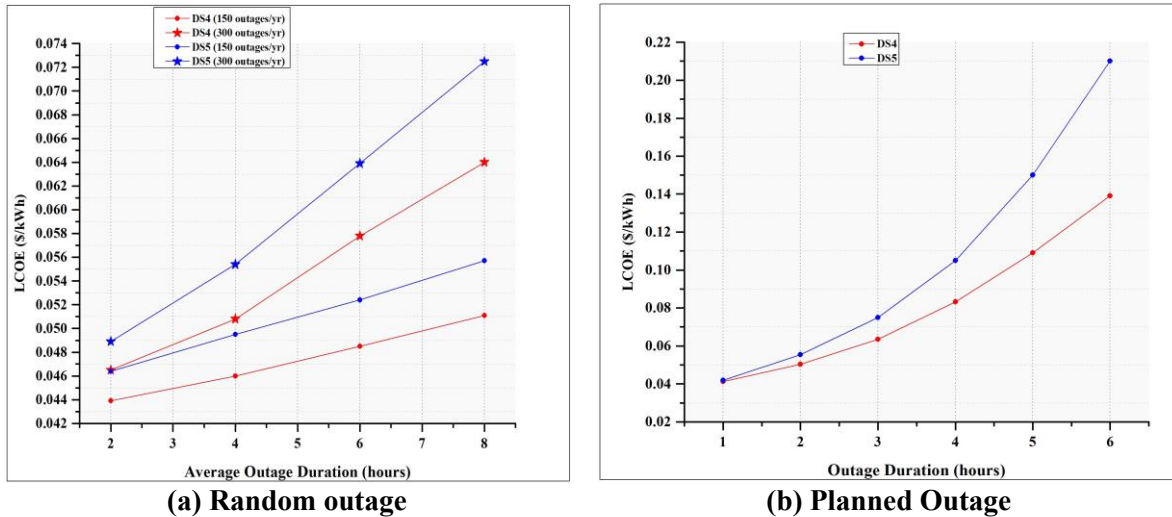


Figure 7.19. Impact of PV capacity on different output parameters for different DSs of PV-grid-battery configuration

grid sales. Due to lesser grid sales, for unreliable grid the LCOE in DS5 was more than DS4 at a particular PV capacity (**Figure 7.19 (a)**). Further, for lower PV capacities, the grid penetration was higher in meeting the demand and charging the battery in both DS4 and DS5 and was highest when PV capacity was 0 %. However, increase in PV capacity reduced the grid penetration resulting in lower grid purchase and higher net grid sales and thus lower LCOE.

7.5.2 Impact of grid outage frequency and outage duration on LCOE for PV-grid-battery configuration

To further comprehend the significance of the two dispatch strategies (DS4 and DS5), a sensitivity analysis was conducted to investigate the impact of annual frequency and average duration of random and planned grid outages on LCOE keeping PV capacity fixed at 66.465 kW (**Figure 7.20**). With increase in both grid outage frequency and average outage duration, the LCOE increased in both DS4 and DS5 due to reduction in grid sales. Further, the LCOE difference between DS5 and DS4 increased with increasing frequency and duration of random outage (**Figure 7.20 (a)**). The highest difference in LCOE was observed for outage duration of 8 hours and frequency of 300 outages where the LCOE in DS5 increased by 13% over LCOE in DS4. The difference was even more prominent for daily planned outages starting from 9:00 am, overlapping with the school demand duration, where LCOE increased by about 51% in DS5 over LCOE in DS4 for daily outage duration of 6 hours (**Figure 7.20 (b)**). Thus, with increase in outages, the reduction in grid sales amplified in DS5 compared to DS4 due to the higher involvement of PV panels in charging the batteries during normal hours in DS5.



(a) Random outage **(b) Planned Outage**
Figure 7.20. Impact of grid outage frequency and duration on LCOE.

7.5.3 Impact of converter capacity on LCOE

To comprehend the impact of variation of converter capacity on LCOE, a sensitivity analysis was conducted keeping the PV capacity constant at 100% in DS2 (**Figure 7.21**). The variation in converter capacity for a particular PV capacity had significant implications on the system LCOE for DSs involving grid sales as it impacts two critical output parameters namely, the total converter costs which increased the LCOE and the grid sales which reduced the LCOE. A low-capacity converter had a low total cost but restricted the grid sales resulting in a higher LCOE. The LCOE decreased with the increase in converter capacity up to 33 kW, as the revenue generated by net grid sales dominated the overall increase in system cost contributed by the converter cost. Beyond 33 kW, the LCOE started to increase as the revenue generated by grid sales was not enough to overcome the increasing system cost due to the converter. Beyond converter capacity of 42 kW, the grid sales revenue became constant as entire excess electricity generated by PV was sold to the grid and any further increase in converter capacity only contributed to increase in the LCOE.

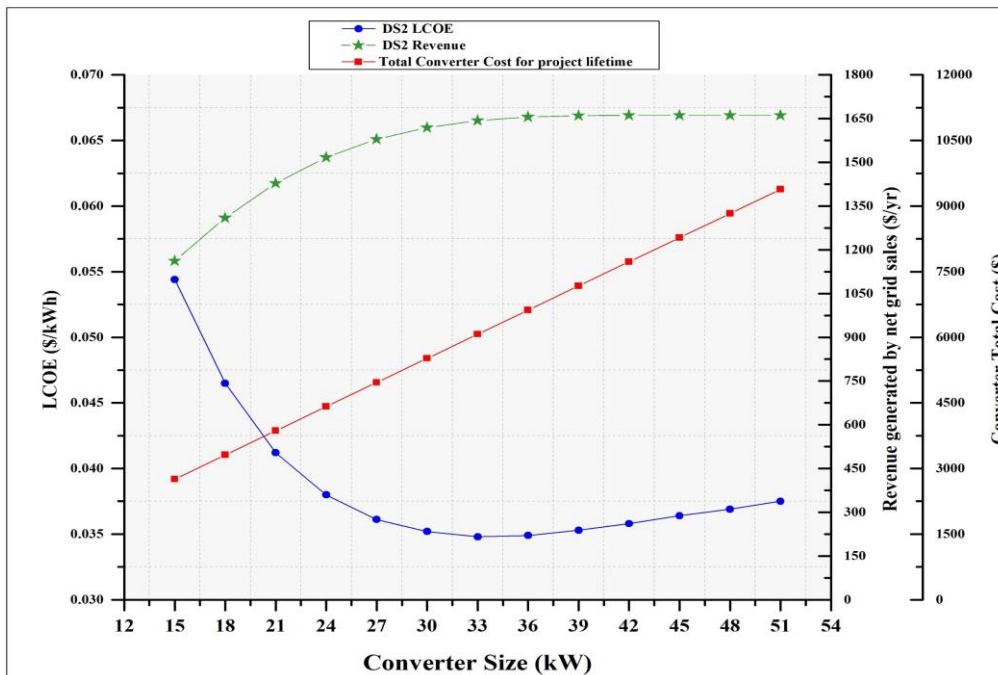
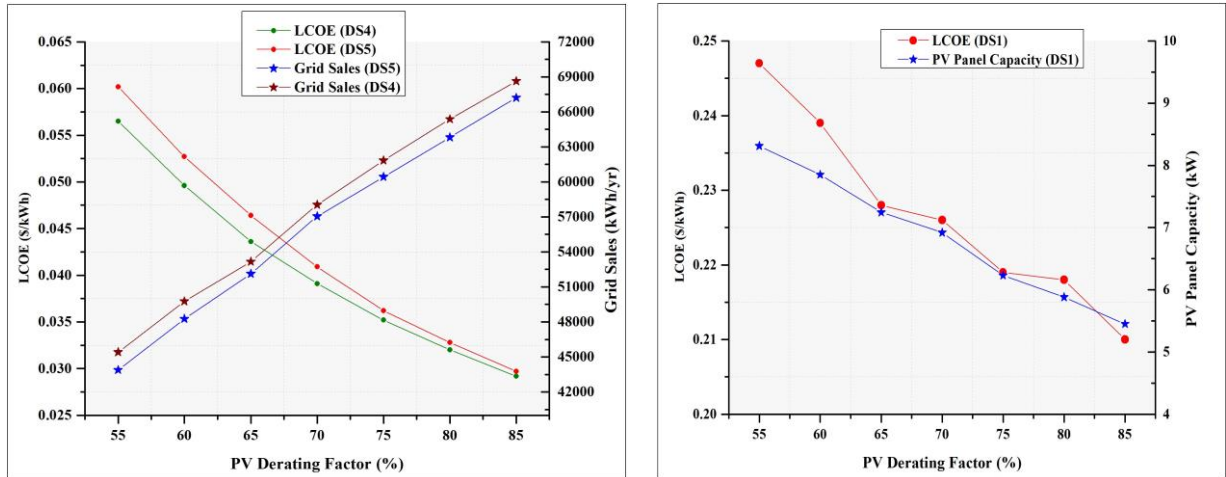


Figure 7.21. Impact of converter capacity on LCOE

7.5.4 Impact of PR on LCOE

The quantitative impact of PR was investigated DS4 and DS5 with PV capacity at 66.465 kW. The impact of PR on DS1 was investigated by using HOMER optimizer for PV panels while keeping other parameters constant. The LCOE decreased by more than 50% with increase in PR from 55 %- 85% in DS4 and DS5 (**Figure 7.22(a)**), mainly due to increase in grid sales with higher PV production per panel. The LCOE similarly decreased by 20% in DS1 (**Figure 7.22(b)**), due to decrease in PV panel capacity with higher PV production per panel.

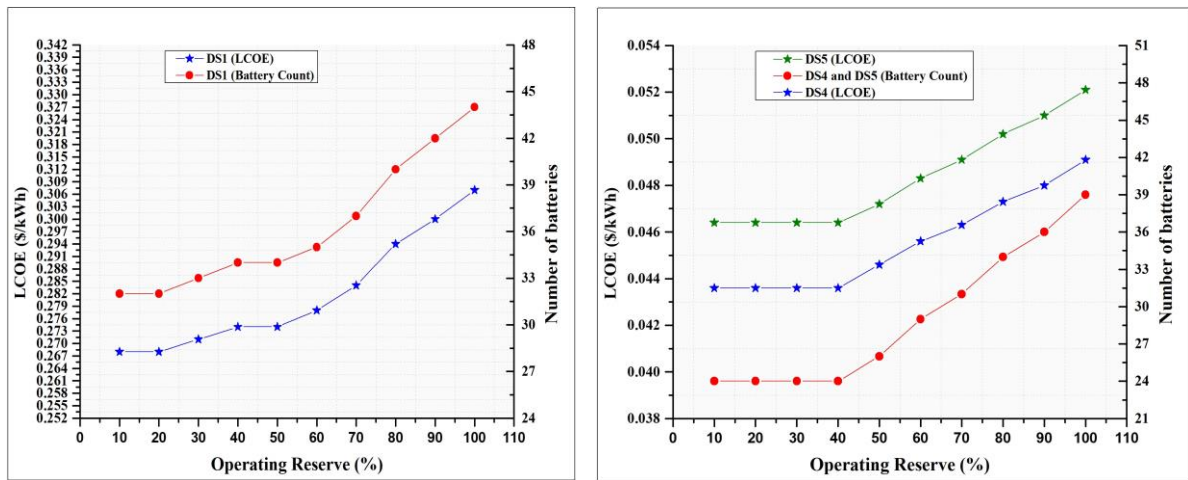


(a) Impact of PR on PV-grid-battery configuration

(b) Impact of PR on standalone PV-battery configuration

Figure 7.22. Impact of PR on the simulation results of the feasible configuration.

7.5.5 Impact of enhancing system reliability on LCOE



(a) DS1

(b) DS4 and DS5

Figure 7.23. Impact of operating reserve (peak load) on LCOE

The system reliability is significant especially for standalone configuration to meet the peak demand, as any sudden increase in demand or any system equipment failure can lead to outage. Reliability can be enhanced by increasing the operating reserve of the system. Operating reserve is excess operating capacity that can promptly respond to an abrupt upsurge in the electric demand or a sudden reduction in the renewable power output. It provides a safety margin that ensures reliable electricity supply despite unpredictability in the electric demand and the renewable power supply. In HOMER PRO, operating reserve is generally ensured by backup devices like battery. In this study, the standalone system was designed at 0% operating reserve and the optimum PV capacity (7.25 kW) was just enough to meet the demand while for grid-connected configurations, PV capacity (66.465 kW) was higher than the minimum capacity needed to meet the demand. The impact of increasing the operating reserve as a percentage of peak load on LCOE was investigated for DS1, DS4 and DS5 (**Figure 7.23**)

by varying the operating reserve. The optimum LCOE increased with increase in operating reserve as the battery count increased in both the cases. The optimum LCOE increased by about 35 % from the current value of 0.228 \$/kWh (0 % operating reserve) when the operating reserve increased to 100 %. In DS4 and DS5, the LCOE and the battery count did not increase till an operating reserve of 40 %, which indicated the PV-grid-battery configuration is reliable enough to handle 1.4 times the current peak load. Beyond 40%, the number of batteries increased and consequently the optimum LCOE increased.

7.5.6 Sensitivity Analysis of Cost Parameters

To have a broader comprehension of the system component costs on LCOE, sensitivity analysis of capital and operating costs of PV panels, batteries and converter and grid purchase and sellback rates on LCOE was conducted for Load Profile 1. A crude survey (21) of upper benchmarks costs and historical and current subsidies along with online and telephonic market survey (212,213) of different components in India was conducted to deduce the minimum upper and lower limits of sensitivity for capital and operating costs for different components while the grid purchase tariffs were considered from (320).

The capital cost for PV panels was varied from 10% to 150% of the present capital cost keeping other parameters constant while the capital costs of batteries and converters was varied between 25% to 300 % of their present costs keeping the other parameters constant. The operation cost was varied between 25% to 200% for each component. Almost linear variations were observed for all the cases.

For PV capital costs, the LCOE varied from 0.019 \$/kWh to 0.0577 \$/kWh for DS4, 0.0218 \$/kWh to 0.0608 \$/kWh for DS5 and between 0.189 \$/kWh to 0.252 \$/kWh for DS1 (**Figure 7.24(a)**) while it varies between 0.0222 \$/kWh to 0.0729 \$/kWh for DS4, 0.025 \$/kWh to 0.0761 \$/kWh for DS5 and between 0.194 \$/kWh to 0.275 \$/kWh for DS1 (**Figure 7.24(b)**) for PV operating costs.

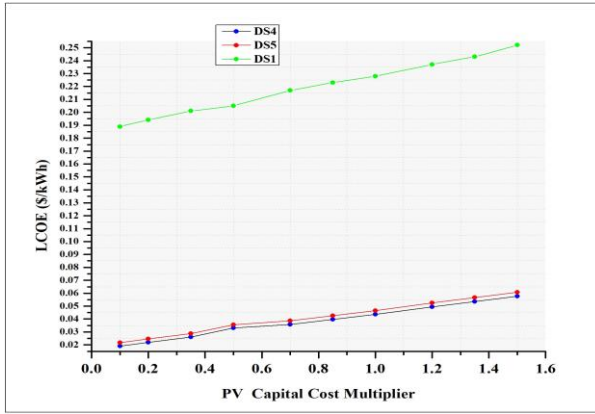
For battery capital costs, the LCOE varied from 0.0417 \$/kWh to 0.0510 \$/kWh for DS4, 0.0431 \$/kWh to 0.0571 \$/kWh for DS5 and from 0.184 \$/kWh to 0.335 \$/kWh for DS1 (**Figure 7.24(c)**) while it varied from 0.0403 \$/kWh to 0.0487 \$/kWh for DS4, 0.0428 \$/kWh to 0.0512 \$/kWh for DS5 and from 0.189 \$/kWh to 0.283 \$/kWh (**Figure 7.24(d)**) for battery operating costs.

For converter capital costs, the LCOE varied from 0.0403 \$/kWh to 0.0537 \$/kWh for DS4, 0.0432 \$/kWh to 0.0567 \$/kWh for DS5 and from 0.212 \$/kWh to 0.277 \$/kWh for DS1 (**Figure 7.24(g)**) while it varied from 0.0424 \$/kWh to 0.0452 \$/kWh for DS4, 0.0451 \$/kWh to 0.0480 \$/kWh for DS5 and from 0.223 \$/kWh to 0.236 \$/kWh for DS1 (**Figure 7.24(h)**) for converter operating costs.

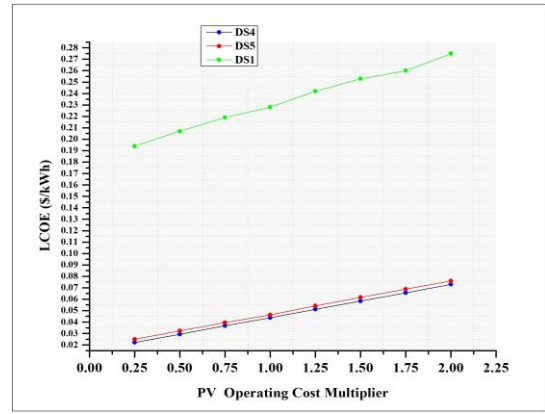
The grid purchase rates were varied between 0.02 \$/kWh to 1.2 \$/kWh for DS4 (**Figure 7.24(e)**) and DS5 (**Figure 7.24(f)**) while the percentage grid sellback rate was varied from 50% to 90% for each grid purchase rate. The LCOE decreased with increase in grid purchase rate at a particular grid sellback rate for both DS4 and DS5. At higher grid purchase rate, the LCOE became negative with increase in grid sales rate beyond 70%. Thus, at locations with higher grid purchase rates and higher grid sellback rates, the grid-tied PV-grid-battery systems can be used to earn profit.

The impact of PV panel costs variations on LCOE variations (percentage) were significantly higher for PV-grid-battery configuration (DS4 and DS5) compared to standalone PV-battery (DS1) due to higher capacity contribution of PV panels compared to battery for PV-grid-battery configuration. Similarly, the impact of battery costs variations on LCOE variations (percentage) were significantly higher for standalone PV-battery (DS1) configuration compared to PV-grid-battery configuration (DS4 and DS5) due to higher capacity contribution of batteries compared to PV panels for standalone PV-battery configuration.

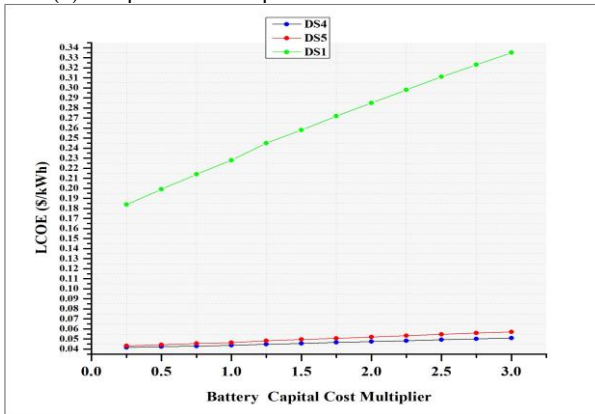
The impact of converter cost variations on LCOE variations (percentage) were almost equal for both the configurations. In DS4, at 300% of the present converter capital cost, the corresponding LCOE (0.0537 \$/ kWh) (**Figure 7.24 (e)**) was 15% higher than the present case-study, LCOE for DS5 (0.0464 \$/kWh). It increased further if converter operational cost increased (**Figure 7.24(f)**).



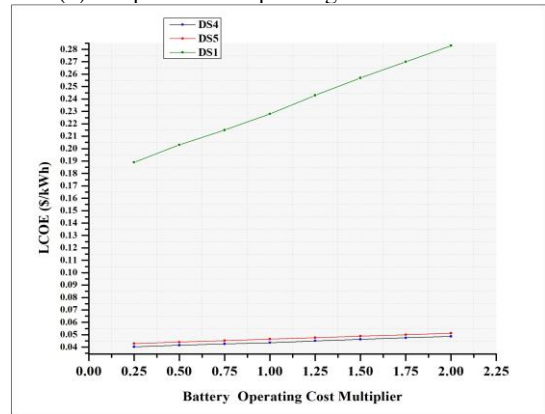
(a) Impact of PV Capital Cost on LCOE



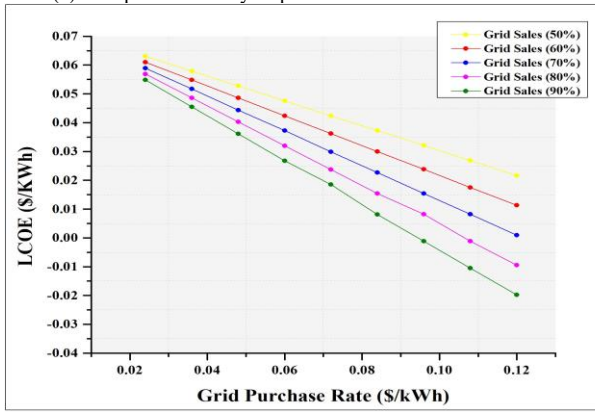
(b) Impact of PV Operating Cost on LCOE



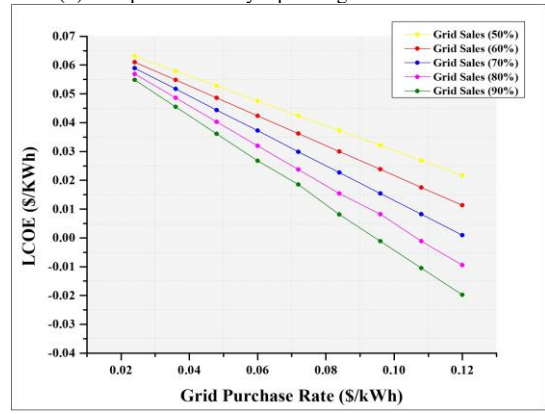
(c) Impact of Battery Capital Cost on LCOE



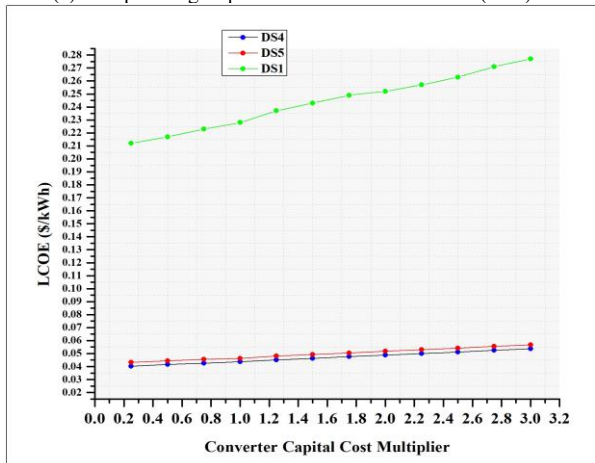
(d) Impact of Battery Operating Cost on LCOE



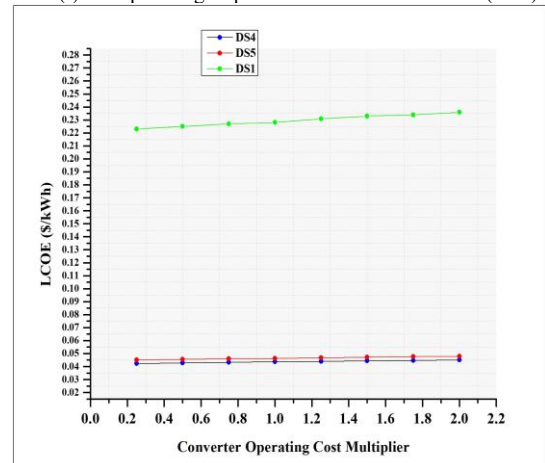
(e) Impact of grid purchase and sales on LCOE (DS4)



(f) Impact of grid purchase and sales on LCOE (DS5)



(g) Impact of Converter Capital Cost on LCOE



(h) Impact of Converter Operating Cost on LCOE

Figure 7.24 Sensitivity Analysis of Cost Parameters on LCOE

Thus, for implementing DS4, the new advanced hybrid converters will be needed which were more expensive than the traditional hybrid converters implemented in DS5. This will result in higher LCOE in DS4 than DS5. Thus, in locations with lower or medium frequency and shorter duration of grid outages, DS5 employing traditional hybrid converters is economically more beneficial, while in locations with higher frequency and longer duration of grid outages (**Figure 7.20**), DS4 employing advanced hybrid converters (DS4) is economically more beneficial.

On simultaneously considering the highest values of capital and operating costs for each component at the present case-study grid purchase and sales rate, the LCOE for DS1, DS4 and DS5 were 0.517 \$/kWh, 0.110 \$/kWh and 0.116 \$/kWh respectively. Thus, it can be concluded that the PV-grid-battery configuration is economically viable and competitive at several locations in India even if expensive components are used and grid tariffs are low. However, the standalone PV-battery becomes economically infeasible with the use of expensive components.

7.5.7 Impact of climatic conditions on LCOE

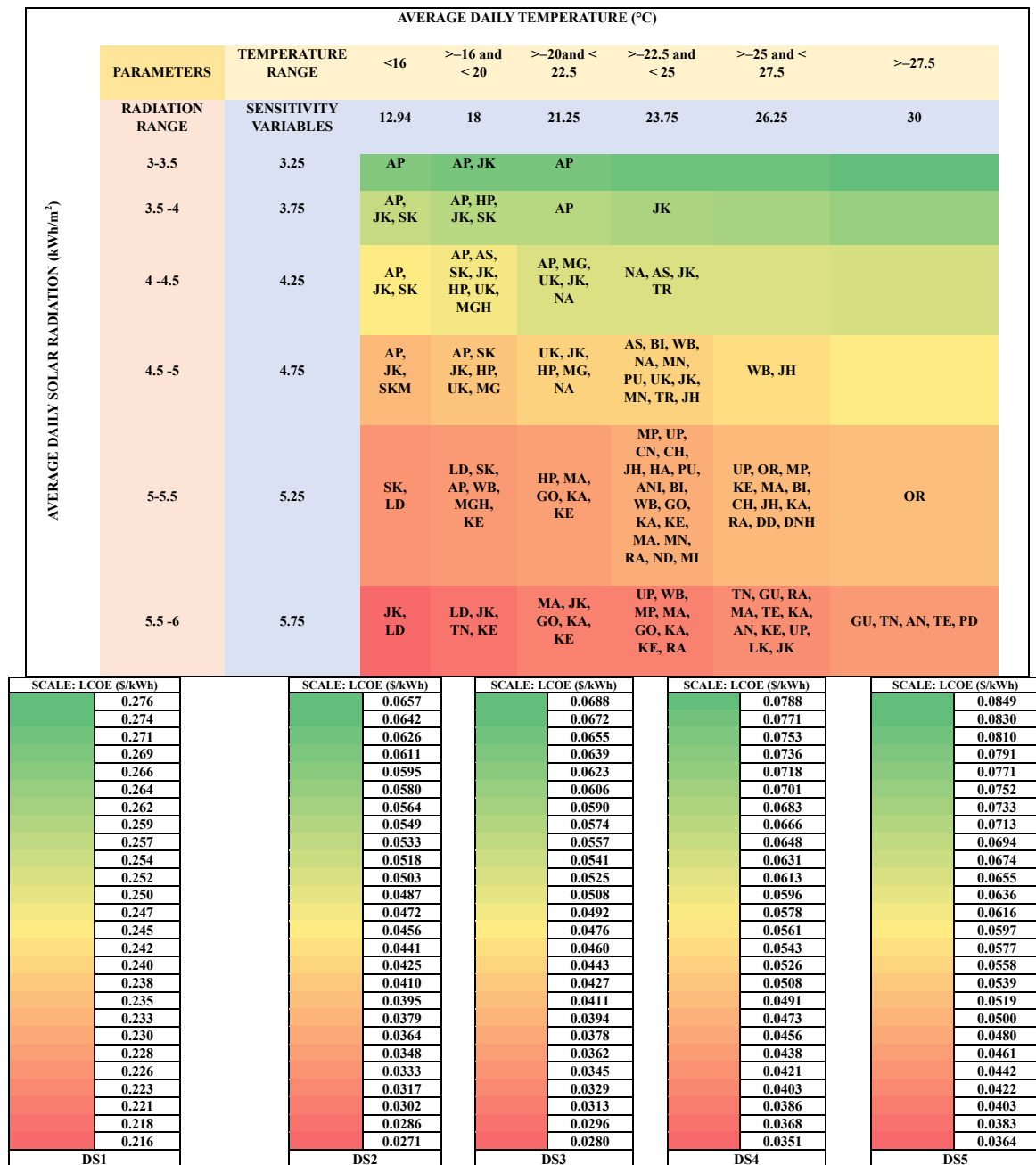


Figure 7.25. LCOE for the system for the school load profile across different locations of India

To have a broader perspective of the economic feasibility of the modelled system for schools across the entire country the system was simulated for Load Profile 1 in various climatic conditions (67) across the entire country of India for PV-battery (DS1), PV-grid-battery configuration (DS4 and DS5) and PV-grid (DS2 and DS3) (**Figure 7.25**).

The LCOE ranged between 0.216 \$/kWh to 0.271 \$/kWh for standalone configuration, between 0.0271 \$/kWh to 0.0655 \$/kWh for PV-grid configuration and between 0.0351 \$/kWh to 0.0830 \$/kWh for PV-grid-battery configuration respectively across various locations in India. Thus PV-grid-battery configuration especially allowing grid sales were quite competitive with grid prices across entire India. The current school location of Sikkim came out as a relatively favourable location for installation of the RTPVS compared to the climatic condition across other states.

7.5.8 Impact of battery degradation on system performance and environmental sustainability

In order to comprehend the impact of battery degradation of Lead Acid Batteries (LABs) on the system performance and environmental impacts, the Idealized Battery Model (184) used in this case-study was replaced by Modified Kinetic Battery Model (184) for which input data like Power vs Capacity curve, Temperature vs Capacity curve and Depth of Discharge vs Cycles to failure are taken from (67,321,322) and sensitivity analysis was conducted by varying the battery degradation limit (%) (184) for DS1, DS4 and DS5. A higher battery degradation limit percentage implies the system can endure a higher amount of battery degradation without replacement(184).

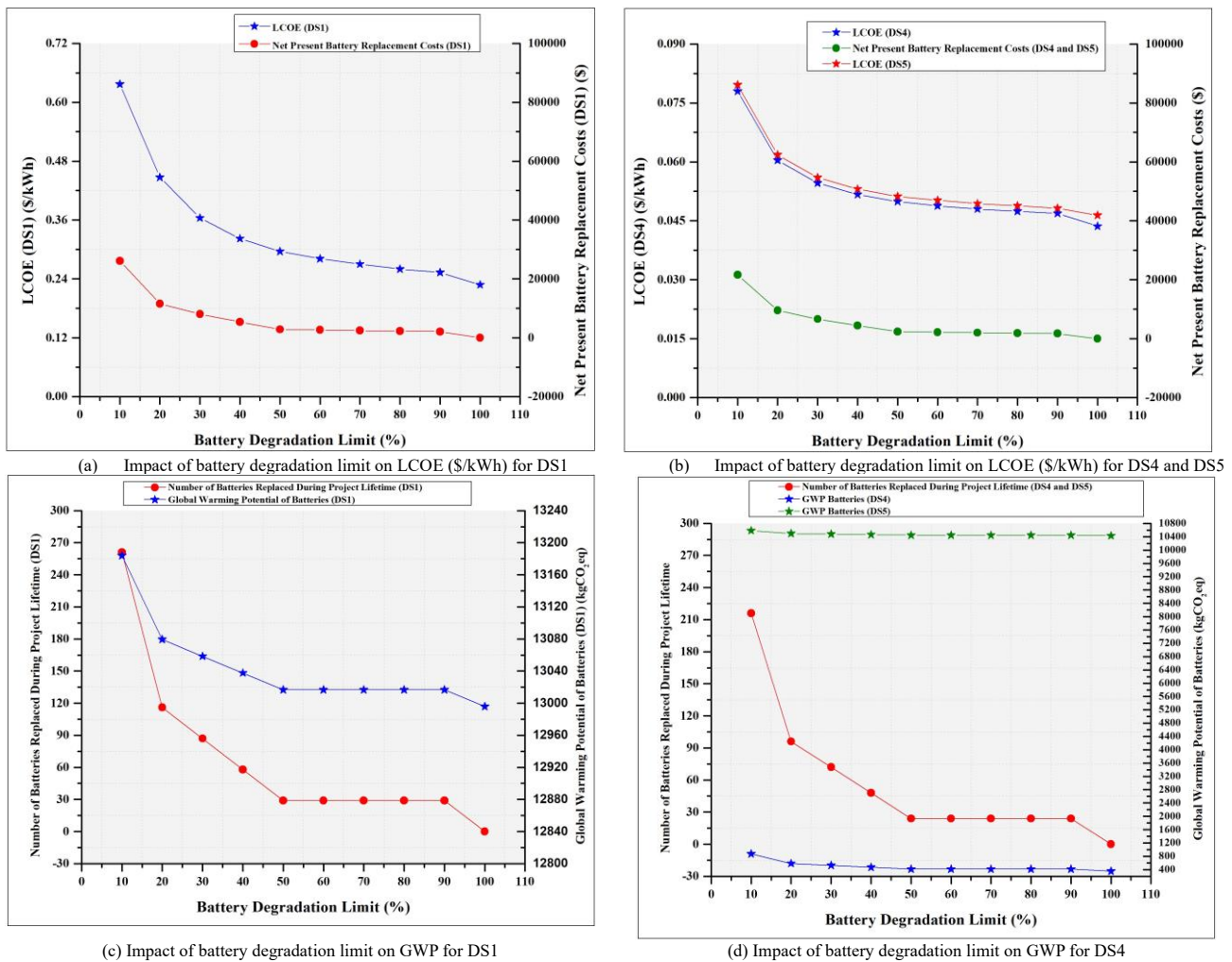


Figure 7.26. Impact of Battery Degradation on Costs and Environment

When the battery degradation limit was 100 %, the system followed the Idealized Battery Model like in the present case. However, with reduction in battery degradation limit (%), the LCOE increased

for both standalone (DS1, **Figure 7.26(a)**) and PV-grid-battery configuration (DS4 and DS5, **Figure 7.26(b)**) as the number of batteries replaced during the battery lifetime increased (**Figure 7.26(a)** and **Figure 7.26(b)**) which increased the net present battery replacement costs. Similarly, the GWP of the system increased due to higher number of batteries used during project lifetime for both standalone (DS1, **Figure 7.26(c)**) and PV-grid-battery configurations (DS4 and DS5, **Figure 7.26(d)**) with reduction in battery degradation limit. Despite the replacement of batteries, the annual battery energy output remained independent of the battery degradation in DS4 and DS5. Since the annual battery energy output has a more significant impact on GWP than the battery replacement, thus the impact of battery degradation on GWP of batteries appeared significantly small for PV-grid-battery configurations (**Figure 7.26**).

7.6 Discussion

Out of the 3 configurations, the PV-grid configuration yielded technically infeasible results with traditional grid-tied converter (DS2) and spatially infeasible results with advanced simulated converters (DS3). However, demand reduction by replacing existing appliances with energy efficient appliances and corresponding system size reduction, availability of more rooftop area or ground area and practical development of advanced converter control systems (DS2) which can island the PV panels to meet the demand even without backup during grid outage, can eliminate the unmet load, making the PV-grid technically and spatially feasible.

Both the standalone PV-battery and PV-grid-battery configuration yielded competitive LCOE at a conservative value PR value of 0.65 for schools across the different climatic conditions (**Figure 7.25**). A higher PR value in locations with lower shading losses will further reduce the LCOE for the configuration (**Figure 7.22**) and enhance economic attractiveness of the configuration for adoption in schools.

Out of the two feasible configurations, the standalone PV-battery configuration has significantly higher LCOE compared to the PV-grid-battery configuration due to the lack of any option of grid sales. Further, the LCOE for the standalone configuration in the present case was higher across entire country when compared to (67) as the power generated by the configuration is consumed only by a single type of user namely, the school in the present case and not shared by multiple diversified users like (67) which reduces the day-to-day variations in load profile and consequently its LCOE. Thus, sharing the excess electricity generated by the standalone configuration in schools with other diversified users like the residential or market sector for the present case may further reduce the LCOE like (67). Despite considering additional cooking appliance replacement costs for standalone system, the LCOE of 0.269 \$/kWh was still lesser than PV-DG-LPG configuration and was not drastically higher than the grid-battery configuration. Further, the standalone configuration outperformed the PV-grid-configuration in terms of GWP indicating its environment friendliness. Thus, the standalone configuration can be a promising option against grid-DG-LPG, DG-battery and also against PV-grid-battery configuration in schools where grid is not available or extremely unreliable with very long outages. Existing and prominent supply scenarios like grid-DG-LPG or grid-battery may be installed only in schools where grid is very reliable and grid operates on renewable energy-based resources and local solar incident radiation is weak or there is no area available for installation of PV panels.

The PV-grid-battery configuration (DS4 and DS5) that supplied electricity at a significantly cheaper LCOE was the best option for schools in India as it outperformed all other options in terms of costs despite of the additional expenditures on energy efficient appliances and e-cooking appliances. It was also environmentally feasible and outperformed the existing supply scenario of grid-DG-LPG configuration in the school and the very prevalent grid-battery configuration used in residential sectors. Further, this configuration can be oversized to increase system reliability without significant increase in costs. For this configuration, traditional hybrid converters (DS5) will prevail economically in medium to low frequency grid outage locations due to higher costs of advanced hybrid converters (DS4). However, advanced converters shall prevail economically in locations with longer duration of grid outages.

The enhancement of system reliability increased the system costs and LCOE in this case-study similar to (285). The oversized PV-grid-battery configuration (DS4 and DS5) turned out to be more

reliable compared to standalone PV-battery configuration (DS1). The additional panels in PV-grid-configuration in PV-grid-battery configuration (DS4 or DS5) which reduced the system LCOE by grid sales during normal grid operations acted as back-up during part system failure (40 %) and made the configuration more reliable without increasing the cost of the system. On the other hand, the standalone PV-battery configuration was designed just to meet the demand and for generating minimum excess electricity. Thus, more panels or batteries were needed to be added as operating reserve in standalone configuration to compensate for even minor system failure which increased LCOE for this configuration.

The PV-grid-battery configuration achieved spatial feasibility in the present study similar to an investigation (319) conducted for a private school in Delhi. However, (319) has employed advanced hybrid converter (DS4), where PV could power the demand during outages and further kept DGs as back up apart from batteries. Further e-cooking was not considered in the demand in (319) which may further impact the spatial feasibility of RTPVS in (319) due to increase in demand.

Despite reduction in average demand by 27%, the LCOE increased substantially with replacement of frequently used unrated appliances with energy efficient appliances in the present case-study unlike (253,256). This is because the present study considered the impact of additional unsubsidised appliance costs unlike (253) which considered subsidized costs and unlike (256) where additional appliance costs were not considered. Further the present study deals with DES unlike (253) where grid is considered. Similarly, the addition of cooking appliances considerably increased the LCOE in this case-study unlike (301) which did not consider additional expenditure in transitioning from gas cooking to e-cooking.

The relation between LCOE with energy demand is constant for grid consumer over a span of time and the overall cost incurred by the consumer is linearly related to the amount of demand. However, the same is not true for the standalone DESs as underutilization of the installed system will result in a higher LCOE for the consumer over the project lifetime. More effective utilization of the DES by sharing the DES with diverse users to reduce the time variations in load demand (load smoothening) and enhance the load factor like (67,323) or use of multiple renewable energy resources in the form of hybrid renewable energy systems to increase the supply side capacity factor like (313), are necessary to reduce the LCOE in standalone DESs. For grid-connected DESs, reduction in demand reduces the LCOE as all the excess electricity is sold to the grid like this case-study and (295).

In this case-study, grid sales in PV-grid-battery configuration significantly reduced the LCOE despite additional costs incurred in appliance replacements and increased the economic attractiveness of the PV-grid-battery system. However, limiting conditions like converter capacity and extensive grid outages as observed in this case and (295,313) may restrict the profitability through grid sales for grid-tied PV systems.

In this case-study, Lead Acid batteries (LABs) were economically viable only as backups for unreliable grid and were not required for a reliable grid, a finding similar to (295), as both studies showed more battery transactions during grid outages. In fact, LAB-backed PV systems were most expensive as per (295) and use of batteries with longer life like Lithium-Ion batteries may further reduce the LCOE. The degradation of LABs and their frequent replacement is another issue as it increases the system LCOE and the GWP of the system as observed in this case-study. The impact of LAB degradation on LCOE and GWP was more for standalone systems compared to PV-grid-battery configuration in this case-study due to the higher percentage contribution of batteries in standalone system compared to PV-grid-battery. The additional maintenance costs required to reduce battery disposal and the battery disposal costs (324–326) may also increase the LCOE further as observed in this investigation (Sec 7.5.7). Despite these concerns, the LABs have been known to perform better than the prevalent and higher energy density Lithium-ion batteries in the context of GWP, metal depletion, fossil fuel depletion and several other environmental parameters (324,327) and hence are still likely to be prevalent in developing countries due to their low capital costs compared to other battery options. Further the recent developments in efficient recycling of essential metals from LABs helps in reduced disposal and reduced depletion of metals during production phase (325,326) will help in increasing its environmental viability.

7.7 Policy Implications

The grid-connected Rooftop PV system connected with battery back-ups with the option for grid sales accompanied by replacement of subsidised gas cooking by e-cooking and conventional appliances with energy efficient appliances can be a promising energy prospect for Indian public schools in terms of reliability, environment sustainability and cost-competitiveness even without any subsidy. Apart from use of traditional hybrid converters, use of advanced hybrid converters where PV can meet the demand during outages will further reduce the costs of electricity in locations with longer grid outages. Locations where grid tariffs and percentage sale rates are high and solar radiation is high, are excellent candidates for this configuration.

Provision of subsidies on energy efficient appliances and on e-cooking appliances similar to LPG subsidy will further reduce the costs and encourage their adaptation in schools. These incentives may also help eliminate the persisting use of firewood for cooking in schools due to rising costs of LPG cylinder. In locations where grid is extremely unreliable or non-existent, standalone PV-battery systems can play a significant role in replacing DG-based systems. Additionally, implementation of policies like carbon taxes and carbon credits (328) will further make both the standalone and PV-grid-battery configurations even more economically attractive.

Thus, currently policy makers who are already promoting rooftop solar (329) and e-cooking for residential sectors (330) can also extend the same for public schools also. On the hindsight, adoption of this initiative on a larger scale by thousands of public schools in India and other developing countries can have significant consequences on the reduction of the GWP of the country as a whole as the grid sales from thousands of RTPVSs installed in schools to fossil-fuel backed grids will reduce overall GWP of the grid itself. The additional demand load generated by e-cooking in schools on the already unreliable grid shall be compensated by school RTPVSs without the need for any further expansion of mega-projects. Reduction of use of firewood and LPG by e-cooking shall also further reduce the GWP. This initiative shall also help reduce the reliance on imported fossil fuels for meeting the electric and overall cooking demand.

To further consolidate policies and remove any form of scepticism among stakeholders (330), additional time-bound experimental investigations on different Indian climatic conditions and locations with different types of panels and batteries, awareness programmes and capacity building initiatives for skill development and employment generation are necessary for the promotion of the proposed strategies. The work may also specifically interest the policy makers of Himalayan states like Sikkim as an alternative solution against further expansion of risky mega hydro-electric power projects (310,311) for sustaining the grid in the region. The findings will also encourage stakeholders of other developing countries who have implemented e-cooking for residential sector to extend it towards public schools and implement RTPVSs in schools to tackle unreliability.

Chapter 8 Conclusion

The present work conducts a feasibility investigation of decentralized energy systems (DESS) for resource rich but grid-outage ridden North-Eastern region of India with an emphasis on Sikkim. The investigation consists of five case-studies mainly governed by the type of load demand, the location and end-use. A combination of renewable energy resources in the form of a hybrid renewable energy system (HRES) or a single resource has been considered for the different case-studies depending upon the convenience and availability of the resource in the location where the case-study has been conducted and other constraints. HOMER PRO software has been used as the main modelling software for the investigation complemented by different innovative methods and techniques depending on the type of problem in the case-study. Independent conclusions drawn from each case-study are detailed below.

8.1 Conclusions for Case-Study 1

In the first case-study, a techno-economic feasibility investigation of a Hybrid Renewable Energy System (HRES) was performed for a township comprising of an amalgamation of academic load, residential load, public utility load and commercial load in East District of Sikkim, India. From the techno-economic analysis, the following conclusions can be drawn:

- Hybrid renewable energy systems (HRESs) are technically feasible for the township location considered in this study in terms of capacity, area usage and costs with PV-Wind-Biogas-Syngas-Hydrokinetic-Battery based HRES being the best system in this analysis with an LCOE of 0.095\$/kWh.
- While modelling an HRES for any location, other important criteria like area usage, emission, employability etc. are also needed to be taken into account along with cost criteria and availability of resources, because the system with least cost of electricity may not provide the best performance in other criteria or a system may be feasible in terms of capacity (technical feasibility) and costs (economic feasibility) but not feasible in terms of area usage (spatial viability) or environmental impacts (environmental viability).
- An HRES consisting of multiple renewable energy resources was found to be better option over single energy resources to supply electricity at no capacity shortage and at lesser cost of energy for a location with space limitations for installation and limitations of resource availability.
- Independently solar, wind and hydrokinetic were feasible while biogas and biomass were infeasible with regards to self-sustainability. Of the feasible sources, hydrokinetic was the cheapest followed by solar and then wind. Further, biogas and biomass-based systems were also operationally the highest GHG emitters among the renewable energy sources and hence their preference ranking went below the other resource-based systems. Wind turned out to be an extremely expensive option for this location.
- Hydrokinetic energy has great potential in this location and further research is needed to be carried out in this regard. However, the limitation of hydrokinetic power is the mandatory availability of a water stream in a nearby location to the end-use like the township in this case. Further regulatory issues related to private use of a public entity like hydrokinetic energy from a river or biomass from forest resource are needed to be considered prior to implementing such resources which may dampen their adoption.

Though with changes in the priority of criteria the best HRES option may be a different one, but the cost of energy is always going to be a top priority for any stakeholder implementing HRESs in any location and in places like hilly terrain locations where finding levelled land is a big issue, lesser land requirement will also be a higher priority for various stakeholders. Hence, this case-study will be helpful in development and implementation of Hybrid Renewable Energy systems in existing and upcoming townships in the Sikkim state and other hilly terrain in the Himalayan region.

8.2 Conclusions for Case-Study 2

In the second case study, a techno-economic investigation of electrifying a grocery shop with an off-grid hybrid renewable energy system (HRES) comprising of photovoltaic panels, wind turbines and batteries was conducted using HOMER PRO software for a location named Majhitar, Sikkim, India where inhabitants face frequent power outages throughout the year. Due to regulatory, environmental issues and social issues associated with other resources, solar and wind were considered for this case. In the absence of smart meters, to generate a quick and more accurate annual load profile than a simple interview-based load profile, RAMP software was used for the demand data generation:

- It has been observed that the PV-battery based system was the cheapest configuration with an LCOE of 0.311\$/kWh while the Wind-battery based system was the most expensive system similar to Case-Study 1 and the PV-Wind-Battery system came in between the two in terms of LCOE.
- In comparison to grid electricity, none of the combination was found competitive simply due to much reduced cost of electricity from grid.
- In fact, the wind-battery system is not recommended for the location due to its outlying expensiveness and large size and poor wind speed in the location while PV-battery based system may be recommended for this location with subsidies or in future with further reduction in capital costs of PV panels.
- The LCOE of the PV-battery configuration ranges between 0.292 \$/kWh to 0.358 \$/kWh across different climatic conditions in India for the grocery shop load profile with Sikkim being a relatively favourable location for its installation.

The limitation of this study was that the space viability could not be analysed as the grocery shop was located in a multistoried building where the rooftop was shared among multiple inhabitants of the building and there is no policy existing regarding its sharing among the commercial outlets on the ground floor of the building and the residential inhabitants at the top floors. However, this study lays a crude foundation for a future deeper feasibility study for electrification of market places with off-grid or grid tied hybrid renewable energy systems which may become competitive as a back-up when compared to diesel generators.

8.3 Conclusions for Case-Study 3

In the third case-study, a comprehensive techno-economic-space feasibility investigation was conducted for an off-grid rooftop PV nanogrid with battery back-up for Rangpo residential suburb of Sikkim. The load data was generated by RAMP software due to unavailability of real data; HOMER PRO was used for simulation and an innovative technique was used to determine the panel area feasibility by dividing the rooftop area equivalently among the residents in a multi-storeyed building. Innovative Cases were investigated to comprehend the results from individual and grouped household's perspective. Correlation analysis was performed to understand the relationships between demand variations, LCOE and panel area requirements of the system. Finally, sensitivity analysis was performed with the generated generic load data (Case 57) generated from the case study for five variable parameters across India, namely, daily solar radiation, daily ambient temperature, average plinth area/household (urban), effective roof utilization factor, monthly electrical demand/household along with battery DOD to realize a broader perspective of this investigation. The following conclusions can be drawn:

- The LCOE of an off-grid PV nanogrid decreases with decrease in day-to-day random variations and time step variations (load smoothing). Thus, off-grid PV nanogrids are recommended for households with higher daily occupancy duration which smoothens the load demand due to more uniform appliance usage and grouped ownership of PV nanogrids (microgrids) for sharing is more recommended than individual ownership which also smoothens the demand.
- The houses with lesser number of dwelling rooms are likely to have a lesser monthly load demand, which may result in a significantly higher LCOE due to more day-to-day random variation and oversizing of components due to unavailability of components of exact capacities in the market or due to higher cost of smaller sized components.
- Low monthly load demand and large plinth area/household and proper rooftop utilization can significantly increase the space viability of off-grid rooftop PV nanogrids even for high-rise buildings.

- The system LCOE for the generic load profile ranges between 0.151 \$/kWh (1\$=73.56 Rs) and 0.195 \$/kWh across the country with lesser values for high global solar radiation and low ambient temperature locations. The LCOE of 0.164 \$/kWh for the present case study in Sikkim also appears favorable compared to several other locations in India. The grid competitive subsidy of 50% obtained for Sikkim may vary across states due to different grid rates and different values of LCOE for the PV system. Presently, MNRE does not provide any subsidy for off-grid PV systems for residential application in India and this investigation may be helpful in that regard.
- The three Sub-Categories of appliance users identified in this case study is a comprehensive representation of the type of appliance users in almost all other urban localities in India due to prevailing work culture in India and thus the generic load profile/household generated in this case study (Case 57) will be applicable to all other parts of the country.
- Operating batteries at higher DOD reduces the LCOE despite a reduction in battery life. At the same capital costs, batteries having higher battery throughput or battery life at higher DOD will reduce the LCOE.
- In the present case study, the space feasibility was conducted for households who do not practice any coordinated demand side management. However, a proper demand side management along with use of energy efficient appliances will reduce the monthly load and the day-to-day load variations, thus reducing the LCOE and increasing the percentage space feasibility. In majority of the states in India (**Figure 5.11**), with effective building roof-utilization factor above 0.37, high rise buildings (>10 storey) with average monthly loads up to 30 kWh/household, mid-rise buildings (5-10 storey) with monthly loads up to 50kWh/household, low-rise buildings (2-5 storey) with monthly loads up to 100 kWh/household, and single and double storey buildings with monthly loads up to 200 kWh/household can install fully autonomous PV nanogrids on their rooftops as indicated by the floor number (FN). For loads beyond 200 kWh/household, detached houses having large number of dwelling rooms and plinth area can adopt PV nanogrids. However, exact results may vary on a household basis as plinth area range of 17 m² to 202 m² for this case-study (**Table 5.10**) exceeds well beyond the state averages.
- **Figure 5.8(e)** and **Figure 5.11** provides a comprehensive overview of various possibilities that can arise in India in terms of techno-economic-space feasibility. On the basis of location (for climatic conditions and average plinth area/household), average monthly load demand/household, the rooftop condition and type of the building, the type of appliance users, the willingness among the end-users to adopt private or shared nanogrid systems, PV nanogrid and microgrid installers can get an approximate idea about the feasibility of an off-grid rooftop PV system in a particular building in that location before undertaking deeper investigations through software dedicated for PV systems only.

Thus, this investigation will provide a comprehensive overview to all the policy makers and prospective stakeholders on several critical aspects prior to exact design and installation of an off-grid rooftop PV nanogrid or microgrid system in different types of residential buildings in urban localities across India.

8.4 Conclusions for Case-Study 4

Case-Study 4 extends the work of Case-Study 3 and tries to comprehend the impact of change of load profile in the same house. In this case-study, a techno-economic investigation was conducted to comprehend the change in the configuration of an off-grid RES comprising of PV panels and battery for electrification of a house with the change in appliance usage behavior prevailing due to the “work from home condition.”

- It has been observed that the work from home condition generated a more uniform load profile leading to a higher load factor and lower percentage day-to-day variations compared to “work from office condition”.
- At the same time the peak load reduced with the “work from home condition” compared to “work from office” condition due to more even distribution of the demand load across the time-period.
- Despite a higher NPC due to higher system size induced by a higher average hourly demand, the LCOE for the system for “work from home” condition was lesser compared to “work from office” condition.

This investigation puts a critical highlight on how sudden change in electrical appliance user behavior leads to change in electrical demand load profile which also leads to change in configuration of an off-grid DES and the LCOE. Similar changes can also be observed in residences where people have retired from their jobs suddenly or in houses where people undergo regular shift changes in their jobs. Thus, it can be concluded that sudden changes in appliance user behavior can lead to drastic change in the electrical demand load profile and the corresponding configuration of an off-grid RES for the same users with the same electrical appliances. This study puts a clear emphasis on the fact that while designing off-grid RES, the sudden and future changes in the behavior of the appliance user also has to be taken into account to realize the system viability over a longer period.

8.5 Conclusions for Case-Study 5

Case-Study 5 investigates the techno-economic-spatial-environmental feasibility of an RTPVS for three configurations, namely, standalone PV-battery, PV-grid and PV-grid-battery for electrification of a school in Chanatar, Rangpo, Sikkim, India. RAMP was used for modelling the existing electric load demand along with e-cooking. PVsyst was used to determine optimum PR and the maximum installation capacity of PV panels which were then used in HOMER PRO for the techno-economic analysis. A total of 5 DSs comprising of 3 in-built HOMER PRO DSs and 2 customized DSs developed in MATLAB, one each for PV-grid and PV-grid-battery configuration were used for techno-economic simulation for both reliable and unreliable grid to analyse the system configuration and performance. Further sensitivity analysis was conducted for impact of PV capacity, converter capacity, grid outage frequency and duration, PR and climatic conditions on the system performance. The key findings are:

- Both standalone PV-battery and PV-grid-battery configurations have an advantage over PV-grid configuration in terms of technical and spatial feasibility in space-constrained and unreliable grid locations.
- Frequent and long grid outages increase the system LCOE substantially for grid-tied configurations by reducing grid sales and can also result in technical infeasibility of PV-grid-battery configuration in space-constrained locations.
- The ability or inability of the PV panels to meet the demand during grid outages, controlled by the type of converter system (DSs) can significantly impact the results for grid-tied configurations. This inability in the PV-grid configuration with traditional grid-tied converters (DS3) makes the configuration technically infeasible even if the system is over-sized and can substantially increase the LCOE for PV-grid-battery configuration with traditional hybrid converters (DS5). Thus, configurations that employ the advanced hybrid converters (DS4), that allow PV panels to meet the demand during grid outages may become economically more attractive over configurations that employ the cheaper traditional hybrid converters (DS5) in locations with high frequency and long duration of grid outages despite the significantly higher capital cost of advanced hybrid converter. On the other hand, PV-grid-battery configurations with traditional hybrid converters are still economically attractive in locations with low-to-medium frequency and duration of grid-outages.
- In PV-grid-battery configuration, the charging of batteries by PV panels should be preferred over fossil fuel-based grid to reduce system LCOE and GWP.
- For a particular PV panel capacity, the converter capital costs and grid sales conflictingly impact the LCOE and their trade-off determines the optimum converter capacity.
- Despite the additional capital costs incurred in purchasing e-cooking appliances and unsubsidised energy-efficient appliances over conventional gas cooking appliances and frequently used unrated electric appliances, the PV-grid-battery configuration with grid sales is a clear winner in terms of costs and emissions than both the school's existing energy supply configuration comprising of grid-DG-LPG and commonly used grid-battery configuration and also competitive against a reliable grid. Despite a much higher LCOE than PV-grid-battery configuration, the standalone PV-battery configuration is the most environmentally viable option and also economically competitive against both the school's existing supply configuration of grid-DG-LPG and grid-battery configuration, and becomes even more economically attractive when grid outages are long and frequent.

- It is economically viable to oversize the PV-grid-battery configuration up to a certain limit by keeping additional batteries and panels for higher grid sales and for higher reliability either when the system components are cheap or there is subsidy on the system or in locations where both the grid tariffs and sellback percentages are high. Similarly, it is economically viable to keep additional batteries or panels for standalone PV-battery systems for higher reliability only when there is subsidy on system components. Additionally, unconstrained PV penetration and grid sales at high percentage sellback rates are necessary to reduce LCOE of the grid-tied configurations and make them competitive against the unreliable grid and for elimination of conventional fuel-based back-ups. Unconstrained grid sales help to oversize the PV capacity in PV-grid-battery configuration without increasing the LCOE, thus making the system more reliable and also reduce the GWP of the fossil-fuel mixed grid.
- The GWP of both the standalone PV-battery and PV-grid-battery are significantly lesser than the existing and prevalent options of grid-DG-LPG and grid-battery respectively in schools. Additional carbon credits introduced in this context and subsidies on e-cooking appliances will further reduce the LCOE for the two PV-configurations and increase their economic attractiveness among the stakeholders.
- Degradation of batteries and their early replacement increases system LCOE and GWP. Despite the detrimental environmental impacts of Lead-Acid batteries, low energy density and shorter life compared to Lithium-ion batteries, LABs are likely to persevere in developing countries due to their low costs, lesser environmental impact compared to Lithium-ion batteries and development of new efficient techniques to recover materials from used-up LABs.
- Overall PV-grid-battery configuration with grid sellback option can be a very promising option for schools all over India unreliable grid locations whose LCOE varies between 0.0351 \$/kWh to \$0.0839 \$/kWh across India with Sikkim being a relative favourable location for its installation. The economic viability of grid-PV-battery configuration realized in this study with a conservative PR value of 0.65 further provides promise for its viability for Indian schools in locations with higher PR.

Thus, this case-study provides an alternative perspective to thousands of public-school authorities and policy makers in different urban and rural locations of developing countries like India which face regular issues of student's withdrawal and absence due to unreliable electricity and are facing difficulty in execution of the PM POSHAN scheme due to rising cooking fuel prices. Further the customized novel DSs developed in MATLAB can be used and modified by other researchers for other resources like wind, hydrokinetic etc for future analysis and development via HOMER PRO-MATLAB link. Future investigation may also delve into impact of non-uniform degradation of different components like batteries or PV panels of a particular configuration on the techno-economic performance of the system. The investigation further links the direct and indirect positive impacts of UNSDG 7 with UNSDG 2, 4 and 13. This investigation will also motivate other sectors to investigate the adoption of RTPVS against grid-DG and grid-battery configurations and e-cooking against LPG cooking.

8.6 Overall Conclusion based on the Case-Studies

Decentralized Energy Systems (DESs) hold promising prospect in future in developing countries like India and especially in complex topography of the North-Eastern Himalayan terrain where transmission losses and long power outages are very prevalent despite having dominantly renewable energy-based centralized mega hydro power projects. However, several aspects are needed to be comprehended for their overall feasibility and their competitiveness with grid. Based on the present study it can be comprehended that hydrokinetic and solar based DESs are two of the most promising prospects in the North Eastern region if energy autonomy is expected out of system. Hydrokinetic energy-based systems though have their limitations marked by site specificness and regulatory issues of rivers. Off-grid DESs can compete with grid in the North-East region either in the form of hybrid renewable energy systems (HRESs) where multiple resources are used. For DESs involving single energy sources like solar, sharing of the DES by multiple types of end-users with varying load profiles will help in reducing the LCOE (Levelized Cost of Energy) as it will smoothen the demand profile by reducing percentage day-to-day variations and also increase the load factor. Alternatively grid-connected DESs with battery back-ups

and with option to sell back to the grid looks most promising in future in this region provided grid outages frequencies are minimal or advanced grid-tied converters are employed. A combined demand of electrified conventional and cooking load can also be possibly met by these DESs if sufficient area is available in the end-use location for their installation. The demand management will always remain a critical aspect in design of these systems for individual type of load or end-user, as it can significantly impact the load factor and percentage day-to-day variation which influences the LCOE and NPC for both standalone and grid-tied systems. The LCOE for the standalone PV-configuration also varies for different load profiles as observed in the different case-studies indicating the impact of load profile on the modelling of DESs. For increasing the space viability of standalone RTPVSs or other DESs in multistoried buildings without additional expenditure on land, the households have to reduce the energy consumption especially the peak demands to ensure reliability of the standalone system or reduced penetration of grid in grid-tied systems. Policy implementation like carbon tax and carbon trading will further enhance the viability of the DESs in future in India and also reduce the imports of fossil fuels for meeting the demand in India.

8.7 Scope of Future Work

Future studies can try to comprehend the impact of addition of electric transportation load apart from conventional and cooking load on the DESs system design. Experimental studies over shorter durations of periods may be conducted with real systems and real resource availability data to understand the variations between these computational investigations and real time performance of the systems. Future studies can also try to comprehend the impact of demand management starting from the building design itself and investigate its impact on the DES system performance and techno-economics. Further studies can also be conducted for biomass and hydrokinetic based systems in these locations. These investigations may be further extended to rural areas with agricultural load demand and locations with larger area availability. The dispatch strategies developed in Chapter 7 can be extended to include other resources.

Each case-study in this investigation independently highlights several critical aspects which will help policy makers, microgrid designers and other stake holders in their work in this region and even at other locations in India as a whole.

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166

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Modeling of an autonomous hybrid renewable energy system for electrification of a township: A case study for Sikkim, India

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ABSTRACT

The present work analyses the techno-economic feasibility of an autonomous hybrid renewable energy system for providing electricity for an academic township in the East District of Sikkim, India. The resources considered for the system were solar energy, wind energy, biogas, syngas and hydrokinetic energy with batteries as back-up. HOMER Pro Microgrid Tool, developed by the National Renewable Energy Laboratory, United States of America has been used as the simulation and assessment tool for modeling performed with hourly data input. Various constraints were implemented to limit the maximum installation capacities of the components considered. All the technical and financial specifications of the components were availed from the local Indian markets. A total of 31 possible combinations of the different resources were analyzed for net present cost, Levelized cost of energy, battery storage, emissions, area requirements and employment potential. The best combination was identified by applying a very widespread multi-criteria decision-making technique named Analytical Hierarchy Process. The Photovoltaic-Wind-Biogas-Syngas-Hydrokinetic-Battery based Hybrid Renewable Energy System was found to be the best combination with a Levelized Cost of Energy of 0.095 \$/kWh. Finally, sensitivity analysis was carried out for various parameters to comprehend the behavior of the system for a broader application in the region.

1. Introduction

Energy shortage in developing nations is one of the biggest problems at present in the world [1–3]. With increasing concerns towards global warming and fossil fuel depletion, the world community has shifted their attention towards exploration of renewable energy resources in the past two decades [1–3]. Renewable energy resources being abundantly available and eco-friendly have potential to provide affordable, sustainable and clean energy to the entire world community and solve the problem of energy deficiency in developing nations. However, the reliability of energy systems based on single renewable energy resources is not enough due to their intermittent availability. A Hybrid renewable energy system (HRES) appears as a promising prospect in this regard. A Hybrid renewable energy system employs multiple energy sources mostly renewable energy resources and sometimes in combination with grid to supply the electrical power demand for a particular region. The advantages of HRESs are that they rely on multiple renewable resources to supply energy which compensates for the unreliability of single renewable energy resources and also reduces the greenhouse gas (GHG)

emissions. They are generally installed very close to the demand location which significantly reduces the chances of transmission wire damages along with ease of access in terms of repair and maintenance.

The power demand in the state of Sikkim in India is increasing rapidly owing to a massive boom of industrialization along with establishment of numerous big academic institutes in the region during the past two decades due to tax exemptions and the perennial Himalayan river Teesta flowing across the entire state. The residential power demand has also increased drastically with a rapid shift of man power to this region due to high job prospects. The state power department has not been able to cope up with the rapidly increasing power demand and this has led to regular power shortages and load shedding in the state. The state also has a complex terrain with hills and rain forests and is prone to natural calamities leading to frequent damage of transmission wires and transformers along the region. The complex terrain of the region makes the repair and maintenance of transmission systems very difficult and time consuming. Many localities, townships in this region and even big industries rely on diesel generators during these phases of power cuts which are expensive in operation due to reliance on conventional fuel and also increasing the carbon emissions in the region.

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Modelling of an off-grid roof-top residential photovoltaic nano grid system for an urban locality in India

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ABSTRACT

In modern era of energy self-sufficiency and its personal preference, an off-grid rooftop solar photovoltaic nanogrid for private use in a single household or among limited number of households poses a promising futuristic prospect. However, several critical aspects need investigation to realize its viability. The present work investigates the techno-economic-space feasibility of an off-grid rooftop photovoltaic nanogrid for residential sector of a cosmopolitan urban locality with unreliable electricity in India. A novel combination of RAMP for load modelling, HOMER PRO for techno-economic analysis and an innovative technique for space feasibility analysis was implemented. 269 houses were surveyed and innovatively classified, based on number of dwelling rooms and demand profile similarity. Correlation and sensitivity analysis were conducted to understand the impact of individual and grouped load profiles, plinth area per household, number of dwelling rooms, climatic conditions, building types and component specification availability in market on the overall cost, configuration and feasibility of the system. Sharing of photovoltaic nanogrids and higher durations of daily occupancy in houses reduce the Levelized Cost of Energy (LCOE) from the system due to reduction in percentage variations of load. The LCOE of shared nanogrids ranged between 0.151 \$/kWh to 0.195 \$/kWh in India. The study recommends 50% subsidy on system capital cost against grid prices. Batteries operated at higher depth of discharge (DOD) and having longer life at higher DOD reduce the system LCOE. Apartments in locations with high annual solar radiation, low annual temperatures, large plinth area, low monthly demand and unobstructed rooftops are good candidates for PV nanogrids. In India, high-rise buildings with monthly loads up to 30 kWh/household, mid-rise buildings with loads up to 50 kWh/household, low-rise buildings with loads up to 100 kWh/household and double-storey buildings with loads up to 200 kWh/household can successfully adopt autonomous rooftop PV nanogrids.

Introduction

Energy shortage, unreliability and its impact on climate change persists as a grave issue in developing countries over the world including countries like India (Agrawal et al., 2020; BBC News, 2022; Chauhan & Saini, 2015; Malik et al., 2020; Phadke et al., 2019) and particularly at remote locations with complex landscapes like the Himalayan terrain (The North East Today, 2020). The power grids in India mostly rely on mega power plants which detriments the environment in the installed location (Chandy et al., 2012; Dhar et al., 2020; Nature NEWS, 2018; Oskarsson & Bedi, 2018; Saidur et al., 2011; Turney & Pthenakis, 2011). The distributed generation systems (DGSs) (Burmester et al., 2017) are likely to solve these issues as they employ renewable energy sources

(RESs), are smaller in capacity and installed near the point of use. The DGSs are classified as microgrids and nanogrids (Burmester et al., 2017). While microgrids are larger in capacity and designed for multiple buildings; nanogrids are designed for a single building or a house (household) which can also be connected with other nanogrids and shared to form a microgrid (Arévalo et al., 2021; Burmester et al., 2017).

With substantial solar photovoltaic (PV) promotion in India (Chosh et al., 2015; Goel, 2016; Tarai & Kale, 2018), hindered by varying levels of willingness and awareness towards its adoption among consumers (Islam & Meade, 2013; Korcaj et al., 2015; Sardianou & Genoudi, 2013), private rooftop PV nanogrids pose a promising prospect in future in congested urban locations. Presently grid-tied PV systems are more

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Modelling of rooftop photovoltaic systems for electrification of public schools in developing countries

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ABSTRACT

The present work investigates the techno-economic-spatial-environmental feasibility of a Rooftop Photovoltaic System (RTPVS) for electrification of a grid outage-ridden, space-restricted public school in Sikkim, India and the techno-economic impact of electric cooking (e-cooking) against gas cooking to tackle rising Liquefied Petroleum Gas (LPG) prices used in Pradhan Mantri Poshan Shakti Niranam (PM POSHAN) scheme, for enhancing student enrolment in public schools. Remote-Areas Multi-energy-systems-load Profiles (RAMF) for load modelling, PVsyst for estimating maximum Photovoltaic panel capacity and optimum Performance Ratio (PR); and HOMER PRO for techno-economic investigation is used. 5 Dispatch Strategies (DSs) are implemented for three RTPVS configurations including two customized HOMER PRO-MATLAB DSs for the grid-connected configurations to understand the impact of employment of advanced and traditional grid-tied and hybrid converters during grid outages. Further, the impacts of transition to energy-efficient appliances, grid unreliability and various sensitivity parameters on the modelled system outcomes are also investigated to generate broader comprehension of the system performance. For unreliable grid, PV-grid-battery configuration with grid sales yields the best feasible result with a lower global warming potential (GWP) and a reduced Levelized Cost of Energy (LCOE) at 0.0548 \$/kWh than both the presently implemented grid-diesel generator (DG)-LPG configuration at 0.306 \$/kWh and prevalent grid-battery configuration at \$0.212 \$/kWh, while the stand-alone PV-battery configuration is also economically competitive at 0.269 \$/kWh with the least GWP. The PV-grid-battery configuration also shows economic viability across entire India for various component costs, grid tariffs and climatic conditions. The optimum converter capacity is conflictingly impacted by grid sales and converter costs. The advanced hybrid converter despite their high costs will be economically more viable over traditional hybrid converters in PV-grid-battery configuration for locations with high frequency and duration of grid outages. The charging of batteries via grid is not recommended as it increases LCOE and system GWP. In locations with high grid tariffs and high percentage sellback rates, the PV-grid-battery configurations can be oversized to increase grid sales and system reliability without impacting the economic viability of the configuration. The degradation of Lead Acid Battery (LABs) increases LCOE and GWP. Policy implementation like carbon credits and subsidies on RTPVS and e-cooking appliances equivalent to LPG may further promote the RTPVS and e-cooking adoption in public schools.

Introduction

Problem

The grid unreliability is a major concern in India which affects all sectors, including schools (Phadke et al., 2019; Graber et al., 2018; Baruah & Basu, 2023). An unreliable grid with frequent power outages can detrimentally impact the teaching quality, student growth and ultimately student enrolment (The Economic Times, 2020; Aemro et al., 2020; Bacolod & Tobias, 2006). Many schools resort to expensive and environmentally polluting DGs while many remain without back-ups (Aemro et al., 2020). To enhance the student enrolment in schools and maintaining the nutritional level of students, the Government of India also implemented PM-POSHAN scheme (previously known as Midday

meal scheme) which has been reasonably successful in the past (Government of India, 2019; Government of India, 2023; Jayaraman & Simroth, 2015; Kaur, 2021). However, lately the cooking of mid-day meal has become unsustainable economically with the rising LPG cylinder prices being a major contributor (The Economic Times, 2021). Consequently, many public schools in India use firewood for cooking midday meals (The Indian Express, 2017) which poses serious health risks and cause environmental degradation (Langbein, 2017; Sihwal & McKay, 2015; French, 1986; Bakehe & Hassan, 2023). Further, the fact that the prevalent LPG itself is a non-renewable energy source and a moderate green-house gas emitter cannot be overlooked in the future (Bakehe & Hassan, 2023; Martínez-Gómez et al., 2016; Islam et al., 2021). E-cooking may be a viable alternative to combat both the rising prices of LPG and the negative effects of traditional method of cooking on people's health and the environment. However, introduction of e-

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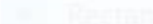
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