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Optimum Utilization of Renewable Energy for Electrification of Small Islands in Developing Countries

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Contents

I dedicate this work to the people of Sundarbans Islands
to whom I owe the spirit, the inspiration and the will
to lead ourselves
from darkness to light

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Abstract

This Doctoral research titled "**Optimum utilization of renewable energy for electrification of small islands in developing countries**" investigated selected themes from the general research question "*What are the impacts of past experiences and present developments on power supply systems on small islands in developing countries utilizing renewable energy and how to improve the situation*?" It focussed particularly on techno-economic aspects and attempted to investigate the state-of-the-art in several aspects of technology, tools and practices for island electrification. It also documented good practice cases concerning technology as well as sustainability. The research developed a generic type methodology for small island electrification with renewable energy and validated it in a real small island in India. It also investigated the impacts of existing island electrification projects on the local society.

The research had a combination of detailed literature review, survey, analysis of real power plant performance, extensive field works in islands, interviews with several authorities, experts, consumers and stakeholders and rigorous computer based energy modelling and simulation exercises. The theoretical, analytical and practical works were documented in six chapters of the thesis to give shape a compendium of discussions on interdisciplinary themes related to island electrification with renewable energy.

The study showed that with appropriate renewable energy technology, organisation and tariff structure the existing projects in the island clusters of Sundarbans in India are creating positive impacts on the islands' society.

The detailed case study was performed for two villages, with a total load of about 98 kW peak and 670 kWh per day, in Bali Island in Sundarbans region in India. In this task, the time series modelling was conducted for power generation via Solar Photovoltaic and Biomass energy technologies. Two optimisation tools, HOMER for power generation and ViPOR for distribution layout, were used in this work and special biomass gasification modules had been developed in HOMER environment. Simulation, optimization and sensitivity analyses had been performed for designing rudimentary power systems. Time and cost saving approach was developed by integrating HOMER-ViPOR combination with remote

sensing and Geographical Information System techniques. Easily available high resolution satellite data were used for preparing suitable inputs accounting for the effect of the spatial features in the distribution layout optimisation tasks.

The research was concluded with optimistic note that many small islands in developing countries through out the world are holding opportunities for greater deployment of renewable energy based electrification in the near future.

Abbreviations used

AMC	Annual Maintenance Contract
COE	Cost of Energy
DEM	Digital Elevation Model
DG	Distributed Generation
DR	Distributed Resources
DSM	Demand Side management
EPS	Electric Power System
ESP	Electricity Service Provider
GIS	Geographic Information System
GTZ	Deutsche Gesellschaft fuer Technische Zusammenarbeit
HRES	Hybrid Renewable Energy Systems
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
INR	Indian National Rupees
IPCC	Intergovernmental Panel on Climate Change
LV	Low Voltage
MDG	Millennium Development Goal
MNRE	Ministry of New and Renewable Energy, India
MV	Medium Voltage
NASA	National Aeronautics and Space Administration, USA
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory, USA
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance
PCC	Point of Common Coupling
PIC	Pacific Island Countries
RE	Renewable Energy
RET	Renewable Energy Technology
RESCO	Rural Energy Service Company
Rs.	Rupees
RS	Remote Sensing
SIDS	Small Island Developing States
SRTM	Shuttle Radar Topography Mission
T&D	Transmission and Distribution
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USA	United States of America
USD	United States' Dollar
VEC	Village Electricity Cooperative
WBGU	German Advisory Council on Global Change
WBREDA	West Bengal Renewable Energy Development Agency, India

Introduction

This thesis is the documentation of major outcomes of my Doctoral research titled "**Optimum utilization of renewable energy for electrification of small islands in developing countries**".

Despite growing usage of renewable energy technologies in small islands, there exist various technical and non-technical barriers for optimum utilization of energy resources for the purpose of electrification. This research study attempts to investigate and support the removal of some of the technological and economic barriers of renewable energy applications for the electrification of small islands in developing countries. The knowledge gained from the study would provide synergy among technology, economics, energy security, environment and sustainable development for the island regions. The results from the study would be able to help island governments, policy makers, planners and scientific communities in future electrification initiatives.

1. Rationale of the research

Energy is accepted as intrinsically linked with environmental, social and economic dimensions of sustainable development. Providing reliable and secure electricity supplies, reducing environmental impacts and providing access to electricity to all has been recognized as the key challenge of the global electricity sector. Energy management is one of the most important aspects an island government has to deal with. Individually, islands may not be very important energy markets with sensible critical mass, but taken together, they are presently the largest niche market in the world for renewable energies (RE). In fact, at present, the largest percentage of the RE in the energy balance is also to be found in islands. On the other hand, the progresses made by islands in developing countries are often found to be inefficient and inappropriate. Question remains about the long-term sustainability of the existing systems as they often become non-functional after few years of installation due to variety of reasons, or they are under-utilizing the potential of RE. In view of this situation, I must admit that present obstacles to consolidate a far-reaching strategy on RE Technologies (RETs) in island regions do not correspond to technological limitations only. There are also political, financial, legal and knowledge barriers preventing the optimum exploitation of RETs, which must be overcome in order to create a favorable socio-economical and technical space. Also there is lack of concern from the governments towards the community living in deltaic and riverine islands. Therefore it is important to have a strong stand to achieve sustainable energy solutions and start working towards this goal in a systematic and purposeful manner. In this regard in-depth study on techno-economic aspects of RETs for electrification in small islands, including deltaic and riverine islands, is important.

2. Objectives

The overall objective of this research study is to support the removal of technical and non-technical barriers for optimum utilization of renewable energies for electrification in small islands.

Some of the specific objectives are listed below:

1. To investigate the state-of-the-art in several aspects of technology, tools and practices for island electrification with optimized RE usage
2. To document the good practice cases regarding RE usage in island electrification projects worldwide
3. To develop a methodology for small island electrification in developing countries with high share of RETs, with a focus on optimization of technological and economic factors
4. To test and validate the basic methodology developed by conducting a comprehensive case study in one selected island of a developing country
5. To investigate the effects of clean and renewable energy based electrification projects on the island life

3. Research questions

There is a world wide trend to utilize renewable energy resources and towards addressing adequate access to electricity challenges in the small islands. It seems that the current developments and trends will influence relevant authorities to adapt more advanced approach which is expected to reflect in the future island electrification initiatives. The general research question investigated by this study can be stated as follows: *what are the impacts of past experiences and present developments on power supply systems on small islands in developing countries utilizing RETs and how to improve the situation?*

It has been attempted to find out the answer to the general question through the answers of the following several specific underlying questions:

1. What is the nature of electrification needs in small islands of developing countries?

2. What are the important operational experiences and issues in island electrification initiatives world wide?

3. What are the suitable power systems, standards, tools and guidelines for island electrification via RET?

4. How is the actual performance of a RE based real distributed generation/micro grid system operating in a small island?

5. What is the nexus amongst various parameters influencing optimal power system in small islands?

6. How to come up with a proposed electrification system in a specific island addressing the real needs?

7. How the electrification initiatives are impacting the island society and addressing the challenges of global environmental change?

4. Methodology used

It is evident from the research questions addressed that this work is rather a compendium of discussions on several themes (as compared to a single research question) related to small island electrification with the optimum usage of renewable energy technologies. This is application oriented research with particular emphasis on techno-economics of electrification systems although it touches multidisciplinary themes.

The study has a combination of extensive literature review, survey, analysis of actual power plant performance data, field work in several islands, interviews with concerned authorities, consumers and stakeholders and computer based modeling / simulation.

5. Structure of the thesis

All components of the study, including theoretical, analytical and practical aspects, are distributed in six chapters.

Chapter 1 sets the scene through an overview of the main issues of island electrification worldwide and establishes the raison d'être of renewable energy for island electrification. Chapter 2 and discusses on tools, standards, power quality issues and power systems for island power supply. Chapter 3 covers discussions on distributed generation and microgrid in the light of potential usage in island electrification. Chapter 4 presents a generic methodology for designing a power supply in small islands which would have optimized amount of renewable energy share. Chapter 5 deals with a real case study in the islands of Sundarbans in India. Chapter 6 covers three topics viz. tariff structures, management models and last but not the least the experience on the effects of electrification initiatives in the island clusters of Sundarbans region in India.

Chapter 1

Electricity from Renewable Energy in Small Islands of Developing Countries

This chapter introduces the theme of small island electrification and addresses the nature of electrification projects using renewable energy in small islands worldwide with a particular focus on developing countries. The method adopted for this part of the research was based on published literature review, surveys and direct communications with various authorities. A Visit to Sundarbans island cluster in India had added values towards understanding the issues. Operational experiences from island electrification projects, key issues and challenges and likely future directions are overviewed here in concise manner.

Energy is recognised as intrinsically linked to environmental, social and economic dimensions of sustainable development. Providing reliable and secure electricity supplies, reducing environmental impacts and providing access to electricity to all has been accepted as the key challenge of the electricity sector worldwide. Energy management is one of the most important aspects an island Government has to deal with. Individually islands may not be very important energy markets with sensible critical mass, but taken together, they represent quite big niche market in the world for renewable energies (RE). In fact, at present, the largest percentage of the RE in the energy balance is also to be found in islands.

1.1. Definitions

Island

The definition of the word island is “A tract of land surrounded by water and smaller than a continent (Source: Merriam Webster’s Collegiate Dictionary)”. The term island in the report renewable “Energy on Small Islands” (2nd edition, august 2000, Forum for Energy & Development) does not cover submerged areas, land areas cut off on two or more sides by water (such as peninsula), or areas land-tied by dam or bridge. It should be highlighted here that there are many locations of the world where a considerable human settlement exist in the deltaic islands and also in islands formed by big rivers.

Small Island

There is no strict quantitative definition of the “smallness”. In the report “Renewable Energy on Small Islands” (1st edition, April 1998, Forum for Energy & Development) a small island had been delimited to an island that is the size or smaller than 600 sq. km. While a medium island having an area up to 10000 sq. km. While the encyclopedia Wikipedia says Small Islands are usually defined as those with an approximate area of 10,000 square kilometers (3,860 square miles) or less and approximately 500,000 or fewer residents [1]. Small islands may include independent islands, archipelagic states and islands associated with or part of larger countries. This helps to generally differentiate them from the larger island nations and states that are rich in natural resource and much more connected.

There are distinctive differences amongst the terms “Small Island”, “Small Island State” and “Small Island Developing State” based on political outlook. In this research thesis whenever this issue came up, exact status mentioned categorically to avoid confusion.

It should be clearly differentiated here that “Island” in an electric power system is defined as part of an electric power system, that is disconnected from the reminder of the interconnected system, but remains energized [2].

Developing Countries

These are countries whose standard of living is far lower than in Europe (excluding Eastern Europe), North America and Oceania (Australia, New Zealand and Japan) [3]. The World Bank classifies national economies on the basis of per capita annual income according to the following thresholds:
low income group = below US$875 in 2005; lower middle income group = US$876 – 3465; upper middle income group = US$3466 – 10725; high

income group = above US$10726. According to the UNDP and OECD, 137 countries from the first three categories are considered developing countries.

1.2. Islands and their special characteristics

Many small islands are highly vulnerable to the impacts of climate change and sea level rise. They are frequently located in regions prone to natural disasters. In tropical areas they host relatively large populations for the area they occupy, with high growth rates and densities. Many small islands have poorly developed infrastructure and limited natural, human and economic resources. Most of their economies are reliant on limited resource base and are subject to external forces, like changing terms of trade, economic liberalisation and migration flows. Often the advice that small islands receive on options for economic growth is based on the strategies adopted in larger countries, where resources are much greater and alternatives significantly less costly [4].

Each island is different in its need for energy. However, some characteristics are unique to small islands compared to the mainland or large islands. Some of them are

- Insularity
- Small markets
- Diseconomies of scale
- Fragility of eco-systems
- Limited range of resources
- Specialisation of economies

Most small islands around the world today are dependent on imported fossil fuels for the majority of their energy needs especially for transport and electricity production. In addition, most small islands have a limited water supply, and water resources in these islands are especially vulnerable to future changes and distribution of rainfall [4].

The majority of islands share the following common energy issues:

- Heavy dependency on imported fossil fuels
- Small scale generation of electricity
- High distribution costs
- Under utilisation of renewable energy sources compared to the potential

Although islands produce only a tiny fraction of global greenhouse gas emissions they are among the most vulnerable to the effects of climate change. Adaptive capacity to climate change is generally low in small islands. Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report had warned that at current rates of greenhouse gas emissions the global climate could warm by 0.2 degree Celsius in a decade, raising the sea level and leading to dramatic consequences for coastal societies in particular. IPCC says “Small islands, whether located in the tropics or higher latitudes, have characteristics which make them especially vulnerable to the effects of climate change, sea-level rise, and extreme events. Sea-level rise is expected to exacerbate inundation, storm surge, erosion and other coastal hazards, thus threatening vital infrastructure, settlements and facilities that support the livelihood of island communities” [4].

In this background, it should be noted here that renewable energy technologies are quite attractive for electrification of islands [5]. Some relevant arguments are listed below

- Islands are highly visible laboratory – in the context of need for RE showcase
- Good RE resources with little fossil fuel reserve
- Island energy security issues
- Demand mainly for domestic, transport and service sector – rarely energy intensive activities

- Smallness of islands make high share of RE possible
- RE power can be modular and decentralised
- Competitive economic advantage: high price of fossil fuels + limited energy demand = higher cost of conventional electricity
- Concerns about environment and climate change

It has been argued by Roper [6] that small island states could set an example on green energy use, thereby contributing to local reductions in greenhouse gas emissions and costly imports.

1.3. Some experiences from Island electrification projects

A comprehensive description of applications of renewable energy on small islands can be found in the publication “Renewable Energy on Small Islands”, Forum for Energy and Development, August 2000. This publication depicts that nearly all islands in the world are totally dependent on fossil fuels. Whereas a very few islands already have usage of renewable energy extensively. Some islands have utilised renewable energy on a big scale. Some islands have set targets of becoming a renewable energy island. All of the mature renewable energy technologies have been utilised for electricity generation on islands. Small islands as well as big islands in regard to area, population and power system have utilised RE and islands in all regions and climates are utilizing RE [7]. More specific findings were as per below:

1. 21% of the islands covered in the publication that are using RE for electricity generation are producing between 25% to 50% of their electricity from RE.
2. Nearly 70% of the islands are producing between 0.7% to 25% of their electricity from RE.

3. Wind power is by far the most utilised renewable energy resource for electricity generation. Over 50% of the islands in the publication that have utilised RE for electricity generation have used wind power.

4. Of the islands producing more than 25% of the electricity from wind power all are (but one) connected by sea cable to another electricity grid.

5. Islands with very big utilisation of renewable energy for electricity production are mainly using hydropower. In the publication more than 50% of the islands with more than 25% of the electricity generated from RE are using hydro power. While over 25% of the islands in the publication utilising RE for electricity generation have used hydro power.

6. Nearly 10% of the islands in the publication utilising RE for electricity generation have used biomass.

European Islands Energy and Environment Network (ISLENET) says "It is in the interest of islands to engage in policies, which favour the promotion of energy management. That is to say, they should consider in their energy planning, the promotion, on the one hand, of energy efficiency and energy saving actions, whilst on the other hand, they should seek to develop, where appropriate, renewable energy sources as means of power. There are of course many obstacles, which impede the development of energy management in islands; however, experience proves that the advantages outweigh the disadvantages". 100% RE island movement was initiated in Samsoe island in Denmark in 1996. Subsequently many other European islands like Pellworm (Germany), Aeroe (Denmark), El Hierro (Spain), Gotland (Sweden), Hiumaa (Estonia), Lemnos (Greece), Achill (Ireland), Ithaka (Greece) etc. had shown interest to utilize more and more RE resources. Scientific community is conducting various pilot schemes and experiments in European islands as well. One example is Kythnos island in Greece. Approximately 2000 inhabitants make the consumption aound 300 kW in winter to 2000 kW during high season. In 1982 it had the first wind park in Europe (5 x 20 kW). Since then a series of development has been carrying on Kythnos power systems. The island power supply is equipped with solar photovoltaic (100 kWp), wind energy converter (5x 33 kW + 1x 500 kW), Diesel generator (5 x 400 kW) and conditioning and control equipments like Battery / converter, phase shifter etc. Installation of three small stand - alone modular hybrid systems and AC coupled systems were done in 2001 and since then running successfully. European islands have grid connected wind power to a great extent. The off-grid situation with solar home systems does not occur as much as in developing country islands.

Publication titled "Renewable Energy Sources in Latin America and the Caribbean: Situation and Policy Proposals", GTZ and ECLAC, May 2004, contains valuable information on Caribbean region's energy situations. An analysis of the renewability of the total supply shows that Caribbean subregion 1 (including Barbados, Grenada, Guyana, Jamaica, Suriname and Trinidad & Tobago) is about 4.7%. While Caribbean subregion 2 (Dominican republic, Haiti and Cuba) has achieved almost 22.8% range [8].

Table 1.1 RE in Total Energy Supply, 2002, Caribbean Region (Source [8])

Country	RE in Total Energy Supply	Hydro	Cane products	Woodfuel residential	Woodfuel agricultural	Woodfuel industry	Char coal	Other RE
Barbados	7%		7%					
Grenada	7%		1%	5%			1%	
Guyana	41%		19.8%	20.2%		0.7%	0.2%	
Jamaica	7.4%	0.8%	3.1%	2.2%			1.3%	
Suriname	19%	13.7%		3.7%		0.2%		1.3%
Trinidad & Tobago	1%		1%					
Haiti	60%	2.7%	2.4%	37%		3%	15.5%	

Dominican Republic	16.1%	1.2%	3.6%	6.3%		1%	4%	
Cuba	20.6%	0.1%	18.6%		1.6%	0.2%		

In Pacific Island Countries (PIC) only about 22% of the population have the access to grid electricity. Existing grids are mostly operated by government owned utilities. About 950 MW of installed capacity is on grid out of which around 58% comes from diesel while hydro contributes around 31%. For off - grid areas small diesel generation as a means of rural electrification is quite common. Though SPV have been used for more than two decades, Kiribati, for example, has 20% coverage by SPV. Total off grid capacity installed so far over the region is about 350 MW. The Pacific region is rich with solar, hydro and bio resources. Some States, like Fiji and Niue, have shown interest to become 100% RE islands in the near future.

There exist considerable population without adequate access to energy in the islands in deltas of big rivers of the world. Sundarbans region in India and Bangladesh contains several deltaic islands between the river Ganges and the Bay of Bengal. In Indian portion, there are 54 islands which are inhabited. There is no conventional electricity supply system in the islands except small diesel grids in very few locations. Most of the major market places have electricity generated by small capacity diesel sets owned by private businessmen. West Bengal Renewable Energy Development Agency (WBREDA), with Ministry of New and Renewable Energy (MNRE), has taken various initiatives to electrify the region [10]. Till November 2005, over 41000 households were using electricity from renewable resources. From tiny solar home systems to half megawatt biomass gasifier, from solar street light to wind-diesel hybrid based medium voltage minigrid, many different systems has been tried there. However, more than 100000 households in 20 islands spread over 131 remote villages within Indian portion still do not have access to electricity at present [11].

Table 1.2 RE capacity available to offset conventional energy used for electricity generation (2003) (Source [9])

Country	Solar				Biomass			Hydro	Wind	Geothermal
	SWH	SHS	Community	Comm.	Agriculture	Forestry	Biofuel			
	(kWe)	(kWp)	(kWp)	(kWp)	(kWe)	(kWe)	(kWe)	(kWe)	(kWr)	(kWe)
Cook Is.	2000	50.7		49.1					40	
Fiji	3000	33.1	8	70	11000	3000	125	90185	75	
FSM	750	41.9	7.8					2060		
Kiribati	50	49	34	10						
Nauru	15									
Niue	20		2							
Palau	500	20	9							
PNG	15000	525	380	200				222000		6000
RMI	75	21	38	2.5						
Samoa	150							11060		
Solomon Is.	150	9	1	25				455		
Tokelau	10			21.5						
Tonga	1000	83.5		20						
Tuvalu	75	2.5	5.6	32						
Vanuatu	225	26.5	36.5	30				600		

The impacts of existing projects are quite positive to the local people. Public enthusiasm and confidence on the usefulness of renewable energy technology is increasing. Positive response, willingness to participate in the project organisation and huge request for new connections from the villagers made WBREDA act aggressively for more electrification drives. As a result several new projects are coming up which includes the first tidal power plant of India. This region also attracts attention of students, researchers and academicians. There exist several publications, over a broad spectrum of themes, based on Sundarbans. From technology to sociology, from energy planning to project finance and management, experts find attractive scopes over vast areas of interest. Undoubtedly Sundarbans created a space of optimism in the minds of other island authorities.

Table 1.3 Existing RE projects in Sundarbans islands (as on 1st November 2005)

(Source [11])

Renewable Energy Projects	Number	Aggregate Capacity	Benefited Households	Population Covered
Solar Power Plant	13	707 kW	3,450	18,400
Solar Home Lighting System	35,000	35 W to 74 W per system	35,000	2,00,000
Biomass Gasifier Power Plant	2	1000 kWe	1,500	9,000
Wind Diesel Hybrid System	1	510 kW	1,000	5,000
Total			40,950	2,32,400

1.4. Key issues and challenges

One interesting fact was mentioned in the publication “Renewable Energy on Small Islands” that nearly 75% of the islands of the report that have utilised renewables were connected formally to a country from the developed world. Thus, by far the majority of RE islands were non sovereign. This situation is gradually changing now and islands from many developing nations have started using RE technologies seriously. Isolated locations in developing countries normally present low income economic activities mostly due to the lack of suitable living conditions and the cost of fuels and commodities. Consequently there is a clear interest of the local authorities and international community to support the development and utilization of local energy resources to improve life quality through sustainable development.

On the other hand, the progress made by islands in developing countries often found inefficient and inappropriate. IPCC reports “The need to introduce and expand renewable energy technologies in small islands has been recognised for many years although progress in implementation has been slow” [4]. Diesel grid or total absence of electric grid is typically found baseline scenario for these islands. Operating RE systems with satisfactory quality and reliability of service itself is technically challenging task there. Despite the fact that the situation differs significantly across islands, problems that characterize small islands generally include very high levels of dependence on fish for food, high-density populations with high rates of growth relative to the carrying-capacity of islands, as well as high rates of urbanization, high dependence on foreign development assistance, a narrow range of available resources, small markets and resulting diseconomies of scale, fragility of eco-systems, lack of sufficient credit and financial resources, and conservatism regarding new technologies. Question remains about the long-term sustainability of the existing systems in developing country islands as they often become non-functional after few years of installation due to variety of reasons, or they are under utilizing the potential of RE. In view of this situation one must admit that present obstacles to consolidate a far-reaching strategy on RE technologies in island regions do not correspond only to technological limitations. Small island energy expert Mr. Thomas Jensen of UNDP thinks that technology alone is not the key issue today. Human aspects including the whole aspect of how energy service delivery is organised are absolutely paramount and keep popping up as a key reason for failure. Institutional structures of such projects quite often become crucial for sustainability. There are also regulatory, financial, legal, social and knowledge barriers preventing the optimum utilization of RE, which must be overcome in order to create a favourable socio-economical and technical space.

1.5. Future trends

RE industry community is seriously considering the future activities in islands. Research and technology development sphere is striving hard to bring continuous up gradation in the electricity generation and supply systems. Bio energy is gradually diversifying its portfolio. Most likely in the mid term timeframe the islands from developing countries would have a high portion from RE bio resources in their energy mix. There is continuous effort to achieve higher energy storage capability as well. The pilot installations of new kinds of ocean and wave energy technologies are already in the horizon.

Perhaps it is needless to mention about the trend that the usage of solar home systems in the future will be gradually replaced with distribution grids charged by renewable resources. For example the European electricity supply system is facing a dramatic transformation in the near future. Distributed generation (DG) will play a key role in this movement. In simple words, distributed generation can be defined as a source of electric power connected to the distribution network or the customer side [12]. This is fundamentally different from the conventional central plant model for power systems. Distributed generation covers fairly broad range of technologies including many renewable energy technologies supplying small amount of power at locations close to the end users. This calls for numerous technical and non-technical challenges. Efforts are being made to address the issues of management of energy networks, the integration of renewable energy resources in the distribution networks, control aspects of generation and load managements etc. These trends result in a number of technical, legal, economic and social challenges [13]. There are several research projects going on which address some of these issues. This is very likely that emergence of distributed generation will bring a trend towards decentralisation in the electricity networks. DISPOWER project report says "In conventional grid structures, electricity is fed into the grid at high voltage levels by relatively few, large power stations, and is brought to the consumer via several intermediate grid levels. As generation becomes more widely distributed, the number of electricity sources increases and the direction of flow can be reversed. The distribution grids assume the function of transporting electricity in different directions and become service providers between generators and consumers. In this scenario, central power stations will continue to exist, but in addition there will be a large number of smaller, distributed systems". Consequently there will be emergence of more distributed control philosophy. European Commission report -"Towards Smart Power Networks" clearly states " Such a control paradigm is provided by Microgrids, i.e. systems at LV that can be operated interconnected to the grid, or in an autonomous way if disconnected from the main grid, providing continuity of supply in case of upstream faults. At MV level, the coordination of several Microgrids and the operation of Virtual Power Plants, i.e. coordination of several DER so that the full functionalities of central power plants are obtained, allows DER to take the responsibility for delivery of security services in cooperation with, and occasionally taking over the role of, central generation" [14]. The outcomes from all these efforts will be very much of relevance to the island energy systems. Today's islands are based on diesel grid or off-grid scenario while tomorrow's islands will follow these technological paradigm shifts. There is a dedicated chapter, Chapter 3, on DG and Microgrids where the issues have been discussed in more details.

Islands are very important and interesting when it comes to the promotion of renewable energy worldwide. There are many successful cases of island electrification through renewable energy. There are good lessons learnt from the failures. Most of the matured RE technologies have been already used in island electrification projects. Learning from the experiences in islands will be useful to the remote locations of the main lands as well. General interest is increasing amongst the island authorities. RE industry is exploring the vast potential still unexploited. There is good reason to be optimistic on the probability of more work in the future for island electrification.

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Chapter 2

Technology for Island Electrification

This chapter addresses some of the important topics concerning technology related to island electrification. It begins with island electrification as a subset of rural electrification and discusses features of rural electrification, role of renewable energy technologies in island electrification and then covers power quality issues and standards, distribution layouts suitable for island electrification and relevant software tools. It is highly probable that the usage of advanced technologies will increase in small islands of developing countries in the future.

2.1. Features of Rural Electrification

Small islands in developing countries very often represent the picture of the remote rural villages in the context of situation. Consequently island electrification in developing countries can be considered as a subset of rural electrification drive in a special sense.

The concept of rural electrification refers to the electricity supply to areas outside of cities. But many researchers have given the concept highly divergent interpretations. Munasinghe [1] notes that rural electrification schemes are often defined in terms of local administrative units, mainly for convenience in implementation. He also observes [2] that most often the term “rural electrification” refers to connections to a central grid. Vogel [3] observes: “according to the international discussion and the understanding of agencies such as the World Bank, the concept of rural electrification does not only refer to strictly rural areas as defined in the country statistics but may also include small to medium-sized towns which are service centres for the surrounding rural areas within a given region”. Many people define rural electrification as “the availability of electricity for use in rural communities, regardless of the form of generation”. Yaron et al [4] simply state: “rural electrification is the process of bringing electricity to rural communities”. Maillard et al [5] state that an exact definition of rural electrification raises the issue of delimiting urban and rural areas. They argue that a differentiation on the basis of statistical data carries with it the danger of inaccuracy because of the differences between countries, and because of the fact that data are often unreliable. Maillard et al [5] proposed the following definition: “rural electrification comprises all activities aimed at enabling users situated outside major cities to have access to electricity. The electrification process can be differentiated from the conventional scheme of extension of a national grid, as it covers everything up to independent configurations supplying power for a specific, determined need, and the solving of specific technical and economic problems”. Mason [6] argues that in all relevant sectors including electricity supply, “rural” suffers from the same definitional problems. One of the consequences of these differences in interpretation is that a comparison between rural electrification projects in different countries is extremely difficult if not impossible. For example, in India the following definition exists: A remote village or remote hamlet will be deemed to be electrified if at least 10% of the households are provided with lighting facility. In addition, energy may also be provided for community facilities, pumping for drinking water supply or irrigation, as well as for economic and income generating activities in the village. Table 2.1 summarizes, for the purpose of mutual comparison, a number of features specific to urban/industrialized supply areas and rural supply areas [7]. The combined effects of the specific features of rural power systems and their more problematic operation and maintenance, make the marginal costs of electricity supply to rural consumers high relative to that of consumers in urban areas.

Energy has multiple dimensions, affecting economic growth, the environment, climate change, national security, and many social concerns, including poverty, population growth, health effects, and gender disparity. At the local and national levels, a reliable energy supply is essential to economic stability and growth, jobs, and improved living standards. Satisfaction of basic needs requires diverse and affordable energy services, and limited access to energy services means that for many people these basic needs are not met.

Table 2.1: Typical features of urban and rural supply areas

(Source: [7])

Feature	Industrial/urban supply areas	Rural supply areas
Area load density (kW/km²)	500 to 100,000	2 to 50
Consumer density (conn/km²)	> 500	1 to 75
Number of consumers per km line length(both MV and LV included)	> 75	1 to 75
Consumption density (kWh/km²)	> 2,000,000	5,000 to 200,000
Total costs/kWh (USct)	10 to 15	Grid based: 12 to 50
		Diesel based: 25 to 100 or more
		PV home systems based: 50 to 500
Investment costs per connection (US$), excl. gen & transm.	<500	500 to 7000, average 1200, extremes of over 100,000
Social aspects	limited	specific financial support and solutions needed
Technical/ organisational aspects	large projects; often heavy power technologies on supply and demand side; reasonable load factors as a result of mixed loads	various technologies and small scale applications; low load factor because of dominant domestic and agricultural loads; intensive customer support needed; ratio of labour to capital high.
Socio-cultural aspects	seldom of importance	important
Economical aspects	profitable business opportunities	limited profitable business opportunities

Energy services include things such as: lighting, cooking, heating and cooling, water pumping, water sterilization, refrigeration, transportation, communication, and electric power for productive purposes. Without access to such energy services, people must spend much of their own time and physical energy on basic subsistence activities, and are limited in their pursuit of educational and income-generating opportunities. In addition, lack of energy correlates closely with many indicators of poverty, such as poor education, inadequate health care, and hardships imposed on women and children.

Rural areas pose particular challenges for energy development because people are usually in remote locations that cannot be connected to the electrical grid. Energy options that do not require connection to the central electrical grid provide emerging opportunities for people in rural areas. The conventional approach for delivering energy services in rural areas has been to use biomass (i.e., burning wood and dung) for cooking and diesel generators for electric power. These options have drawbacks related to resource depletion, land degradation, air pollution, and reliability. The challenge is to supply rural areas with energy services that not only are good for the environment, but also provide social and economic benefits. Many institutions, including major utilities, have begun to question the validity of rural energy development models based solely on large, centralized units and the inevitability of ‘economies of scale’ in generation, delivery and end-use. Instead, designs that use smaller, modular units in a localized area that are more environmentally sound are being viewed as the more appropriate option in rural areas. Renewable energy systems meet these criteria and can be the key to improving the delivery of energy services in developing countries. The range of available technologies and applications involve tapping into the sun, wind, water, and organic matter to provide local power to rural communities cost-effectively and reliably as well as create jobs and build new businesses.

The World Energy Assessment [8] says “The amount of energy needed to satisfy the basic needs of rural populations around the world is relatively small, and appropriate technologies are available. Yet of the 3 billion people living in rural areas of developing countries in 1990, 2 billion were still without access to electricity. However, widening access to modern energy services is limited by the extreme poverty found particularly in the least developed countries. Living standards in rural areas can be significantly improved by promoting a shift from direct combustion of biomass fuels (dung, crop residues, and fuel wood) or coal in inefficient and polluting stoves to clean, efficient liquid or gaseous fuels and electricity”. The dispersed character of rural populations and their low commercial energy consumption result in poor capacity utilization efficiency for transmission and distribution systems and other energy infrastructure. Extending an electric grid to a few households in a rural setting can result in energy costs of up to $0.70 per kilowatt-hour, seven times the cost of providing electricity in an urban area [8]. Thus conventional approaches to extending energy infrastructure are economically inefficient, for both public and private providers—which is another reason the energy problems of rural populations are given low priority by governments. Satisfying basic human needs with modern energy carriers requires relatively small amounts of energy in absolute terms. In regions that do not require space heating, final household energy requirements for satisfying basic needs are estimated to be about 2,000 kilocalories per capita per day or 0.1 kilowatt per capita in average power provided (80 percent for cooking and 20 percent for electricity, [8]). The cooking needs of the 2 billion people not served by modern fuels correspond to about 120 million tonnes of oil equivalent of LPG a year—which equals 1 percent of global commercial energy consumption or 3 percent of global oil consumption. This is less than is currently lost flaring natural gas in oil fields and refineries. A relevant example is about India where India alone accounts for more than 35% of the world's population without electricity access. This is described in details in chapter 3.

Electricity is at the top of the energy ladder and for lighting, communication, refrigeration, and motor applications electricity is essential for a satisfactory quality of life. Moreover, electricity is the key to improve agricultural productivity through mechanisation and is essential for many rural industrial activities. Considerable progress has been made in rural electrification programmes designed to extend electricity services to isolated villages. The table 2.2 gives some figures from WEA [8]. It should be noted that access includes people living in villages connected to power lines. This does not necessarily mean that most households are hooked up to electricity. Access to energy was a high priority in the World Summit on Sustainable Development in Johannesburg on August 2002. In 2002, more than 1.6 billion people had no access to electricity out of the total population of around 6.2 billion. About 2.4 billion relied only on primitive biomass for cooking and heating [9]. In 2002 about half of the world population lived in rural areas including almost 90% (approximately 2.5 billion) in developing countries. Among them approximately 1 billion people were located very close to existing electric supply network. Another 1 billion people were located very far from any electric supply network. The rest i.e. about 500 million people were not very far from existing networks [10].

Table 2.2: Global Access to electricity 1970-1990 (Source: [8])

Global Population & access to Electricity (Millions of people)			
Population	1970	1980	1990
World Population	3600	4400	5300
Rural Population	2600	3000	3200
With access to electricity	610	1000	1400
Without access to electricity	2000	2000	1800
Percentage of rural population with access	23	33	44

On the centralised approach to provide access to electricity, the WEA [8] states "Rural electrification programmes have typically concentrated on connecting villages and remote areas to a national grid—often owned and operated by a public utility. The tendency has been to extend the grid incrementally, reaching towns and settlements in order of increasing capital costs. Thus remote areas with small populations are likely to be the last to receive electricity. Moreover, many rural areas face high transmission and distribution costs, for several reasons:

- The capacity of power lines is inefficiently used because of low population.
- Densities and demand levels are low.
- Villages may have very peaky (undiversified) demand profiles.
- Line losses tend to be high.

In addition, incremental extension of the grid (rather than extension optimised to minimise losses) causes lines to be strung haphazardly, resulting in greater losses". Because of the problems of supplying grid electricity for small, scattered, peaky loads, decentralised electricity generation is becoming more attractive. With decentralised systems, the high costs of transmission and distribution networks can be avoided. Thirault et al. [10] observed the following points about the difference between developing and developed countries for rural electrification

- Daily electricity
- Population and demand density
- Remoteness of existing medium voltage line
- Very peaky (undiversified) demand profile

2.1.1 Renewable energy based island electrification

As mentioned in the Chapter 1 electricity generation technologies which are common in islands are small scale hydro power, wind, photovoltaics and small scale biopower using producer gas besides fossil fuel operated diesel engine – generator sets. Table 2.3 summarises some technological options in general for different time ranges.

Renewables 2005 Global Status Report [11] observes “Village-scale mini-grids can serve tens or hundreds of households. Traditionally, mini-grids in remote areas and on islands have been powered by diesel generators or small hydro. Generation from solar PV, wind, or biomass, often in hybrid combinations including batteries and/or a supplementary diesel generator, is slowly providing alternatives to the traditional model, mostly in Asia. Tens of thousands of mini-grids exist in China, primarily based on small hydro, while hundreds or thousands exist in India, Nepal, Vietnam, and Sri Lanka. The use of wind and solar PV technologies in mini-grids and hybrid systems is still on the order of a thousand systems worldwide, mostly installed in China since 2000”.

In this thesis special attention is given to mini and micro grids powered by photovoltaics and biomass gasifiers along with traditional diesel engine generators in Distributed Generation (DG) philosophy environment. Distributed Generation concept is discussed in chapter 3. As described in details in Chapter 4, the methodology developed in this present research on “Optimum Utilisation of Renewable Energy for Electrification of Small Islands in Developing Countries” is not limited by those specific generation technologies. Rather the aim was to achieve a generic solution pattern. However, while conducting the methodology validation case study in a real island, the focus was automatically narrowed down to the specific technologies viz. PV and biomass gasification as per the local situations prevailing.

Table 2.3: Some technological options for rural energy (Source:[8])

Energy source or task	Present	Near term	Medium term	Long term
Source Electricity	Grid or no electricity	Natural gas combined cycles, biomass-based generation using gasifiers coupled to internal combustion engines, photovoltaic, small wind, small hydroelectric for applications remote from grids	Biomass-based generation using gasifiers coupled to micro-turbines and integrated gasifier combined cycles, mini grids involving various combinations of photovoltaic, wind, small hydroelectric, batteries	Grid-connected photovoltaic and solar thermal, biomass-based generation using gasifiers coupled to fuel cells and fuel cell/turbine hybrids
Fuel	Wood, charcoal, dung, crop residues	Natural gas, LPG, producer gas, biogas	Syngas, DME	Biomass-derived DME with electricity coproduct
Cogeneration (combined heat and power)		Internal combustion engines, turbines	Microturbines and integrated gasifier combined cycles	Fuel cells, fuel cell/turbine hybrids
Task Cooking	Woodstoves	Improved woodstoves, LPG stoves, biogas	Producer gas, natural gas and DME stoves	Electric stoves, catalytic burners
Lighting	Oil and kerosene lamps	Electric lights	Fluorescent and compact fluorescent lamps	Improved fluorescent and compact fluorescent lamps
Motive power	Human- and animal-powered devices	Internal combustion engines, electric motors	Biofueled prime movers, improved motors	Fuel cells
Process heat	Wood, biomass	Electric furnaces, cogeneration, producer gas, NG/solar thermal furnaces	Induction furnaces, biomass/solar thermal furnaces	Solar thermal furnaces with heat storage

2.2 A Short Note on Power Quality for Island Electrification

As yet, special technical features for stand alone grids have not been treated in detail in norms and regulations. Examples of widely extended conventional applications of stand alone grids include industrial grids, supply systems on ships and uninterruptible power supplies. Renewable electricity based stand alone supply in the context of island electrification is of importance to this research study.

The load of an electric device is rated at its nominal voltage, but many electric appliances and devices have an electric load that varies as the supply voltage is varied. Generally, loads are grouped into three categories depending on how their demand varies as a function of voltage, constant power (demand is constant regardless of voltage), as a constant current (demand is proportional to voltage), or as a constant impedance (power is proportional to voltage squared). The load at a particular consumer or in a particular area might be a mixture of all three. Incandescent lighting, resistive water heaters, stovetop and oven cooking loads, and many other loads are constant impedance loads. Electric motors, regulated power supplies, and some other loads are constant power. As the voltage drops, the devices make up for that loss by drawing more current, so the voltage times current product remains constant. In addition to actual constant power loads, all loads downstream of a tap changing transformer appear to the power system as relatively constant power loads and are generally modelled in this manner [12]. There are a small number of devices that are constant current loads. They draw power in proportion to the voltage. Some types of welding units, smelting and electroplating processes are constant current loads. However, constant current loads constitute a small minority of electric devices. Electric loads are almost always represented as at nominal voltage. Constant impedance, power and current loads of 1,000 watts all create exactly that level of demand at 1.0 PU (per unit) voltage, although they would differ at other voltages because of their different voltage sensitiveness. In the context of small, remote islands in developing countries, mostly the loads will be of constant impedance type. Very often the contribution from motive load (constant power) is insignificant.

In off-grid operation, the output waveform becomes important for many applications. Square wave inverters may be used to power resistive type loads such as light bulbs. When feeding power to reactive type loads such as motors, proper operation might become difficult and losses inside the load created by the square wave character of the supply might occur. For these load types, ideal sinusoidal voltage supply is the best. In reality, a compromise between this ideal voltage that results in high expenses and a lower quality for cheaper investment requirement must be found.

The deviation from the ideal sinusoidal voltage is normally described as total harmonic distortion (THD). THD is usually defined as the ratio of the square root of the sum of the squares of the RMS values of the harmonics to the RMS value of the fundamental. This ratio is usually converted to percent or decibels (dB). For high quality power supply, the THD of the output voltage should be less than 5%, which corresponds with the quality of the public grid. As a second important power quality element for off grid applications, the ability to provide and to absorb reactive power should be considered. Typical loads requesting reactive power are electric motors. In some inverter designs, handling of reactive power is limited depending on the load type. In this case, the acceptable power factor, which corresponds with the cosine of phase angle difference between voltage and current, is defined and the maximum power of the inverter is given in kVA instead of kW. The energy of the reactive power, which is to be absorbed and afterwards re-injected into the load, is normally stored in capacitors of appropriate size. If all the elements in the inverter allow for reverse power flow, a bi-directional inverter is obtained, which can be used to charge the battery, when surplus power at the AC side is available.

Stand-alone inverters should also be able to blow fuses in cases in which a short circuit occurs in loads. This requirement is perfectly fulfilled with only a few inverters. The reason being the high current needed to blow fuses. Depending on the reaction time, this current can be as high as five times the nominal value. Some inverters produce this high current by reducing the AC output voltage significantly. The resulting flicker observed for loads not to be separated by the fuse in question may be accepted in most cases.

In this point, it can be mentioned here that there are several international standards available in the related fields and some of are being developed now. A few of them are listed below

- IEC /TR2 61836:1997. Solar photovoltaic systems – Terms and symbols.
- IEC 61724:1998. Photovoltaic system performance monitoring. Guidelines for measurement, data exchange and analysis.
- IEC/PAS 62111:1999. Specifications for the use of renewable energies in rural decentralized electrification.
- IEC 62257-1 TS Ed. 1.0 Recommendations for small renewable energy and hybrid systems for rural electrification – Part 1: General introduction to rural electrification

- IEC 62257-2 TS Ed. 1.0 Recommendations for small renewable energy and hybrid systems for rural electrification – Part 2: From requirements to a range of electrification systems
- (Draft)IEC 62257-3: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 3: Project development and management
- (Draft)IEC 62257-4 TS ED.1 - Recommendations for small renewable energy and hybrid systems for rural electrification - Part 4: System selection and design
- (Draft)IEC 62257-5 TS ED.1 - Recommendations for small renewable energy and hybrid systems for rural electrification - Part 5: Safety rules - Protection against electrical hazards
- (Draft)IEC 62257-6 TS ED.1 - Recommendations for small renewable energy and hybrid systems for rural electrification - Part 6: Acceptance, operation, maintenance and replacement
- IEEE 1547 – Standard for interconnecting Distributed resources with electric power systems
- IEEE P1547.1 - Draft Standard for Conformance Test Procedures for Equipment interconnecting Distributed Resources with Electric Power Systems
- (Draft) IEEE P1547.2 - Application Guide for IEEE Std.1547 Standard for Interconnecting Distributed Resources with Electric Power Systems
- (Draft) IEEE P1547.3 - Guide for monitoring, information exchange and control of distributed resources interconnected with electric power systems
- (Draft) IEEE P1547.4 - Guide for design, operation, and integration of Distributed Resource Island Systems with Electric Power Systems

The general aim of power delivery in island electrification should be to have as high quality as possible towards reaching normal low voltage grid norms and to consider the nearest possible similarity is the case of low voltage public grid in the grid connected main land. However, it is not always possible for renewable energy based stand alone grids to maintain all the limits strictly as per the norm developed for conventional low voltage grids. Stand alone renewable energy power systems are usually characterized by weak grids where frequency variations are more intense than as in interconnected grid systems. The frequency and voltage deviations, if they do not happen too frequent and too long, are usually acceptable for most of the applications in a small island context. Utilities should not aim to provide flawless service, which would be prohibitively expensive, but instead aim to provide the highest level possible within economic constraints of the consumer's willingness to pay.

Some of the electrical features of low voltage grids based on the European Norm 50160 / 1994 are summarized below:

EN 50160: "Voltage characteristics of electricity supplied by public distribution systems"

In general, EN 50160 defines the main characteristics of the voltage at the customer's supply terminals in public low voltage and medium voltage distribution system and gives the limits or values within which any customer can expect the voltage characteristics to remain under normal operating conditions. This standard does not apply under abnormal operating conditions.

Frequency

50 Hz +/- 2 % during 95% of the time for each weekly interval

50 Hz +/- 15% during 100% of the time for each weekly interval

Supply voltage

230 V AC

Slow voltage variations

95% of the rms voltages (10 minutes average values) have to be within the range of +/- 10% for each weekly interval

Fast voltage variations

Fast voltage variations up to 10% could occur many times per day

Voltage dips (voltage variations greater than 10%)

Voltage dips are normally shorter than 1 sec and smaller than 60% of rated voltage. Lower voltage dips which are smaller than 15% can occur more frequently.

Flicker range

The flicker factor in 95% of the time for each weekly interval has to be smaller than 1.

Short interruptions in supply

Recommended values: The number of interruptions per year has to be smaller than 10...100; the duration in 70% of all cases has to be smaller than 1 sec.

Long interruptions in supply

Recommended values: unannounced interruptions, shorter than 3 minutes, have not to exceed the number of 10- 50 times per year.

Over voltages at line frequency

The over voltages must not exceed the rms value of 1.5 kV.

Transient over voltages

Peak values must not exceed the value of 6 kV. The energy content of the over voltages is case specific.

Voltage unbalance

Recommended values: 95% of the 10 minutes average rms values of the negative direction component must be smaller than 2- 3% of the positive direction component.

Harmonics

95% of the 10 minute average rms values of the harmonics in the voltage have to be smaller than 5%. The total harmonic distortion (THD) can not exceed 5%.

Interharmonics

No limit had been defined.

2.3 A Short Discussion on Power Supply Systems for Remote Island Electrification

The exact layout of a suitable power system in a remote island depends greatly on the specific situation, the design standards and practices in effect, local conditions etc. amongst many other factors. In this section some technical issues like the suitability of overhead wire or underground cable, single phase or three phases, American or European system of distribution layout etc. are highlighted here very briefly.

2.3.1 Preliminary overview

For remote villages DC distribution may not be of interest for the present study and henceforth only AC power distribution is considered. Underground feeder construction is used both in dense urban areas as well as suburban applications, both for aesthetic and reliability reasons [12]. Relatively cheaper overhead lines are very commonly used in remote rural electrification in developing countries. Since the focus in this report is on small and remote islands in developing countries, overhead AC distribution system is considered to be the suitable for electricity supply. Similarly high voltage AC or DC transmission is not considered in this research study.

In a typical remote island the load will be mostly domestic type and hence single phase. The three phase loads normally involve motor applications in water pumping and other industrial applications which require big amount of electric power to be consumed. In the scope of this study such kind of loads are expected to be very less and henceforth three phase end usage is not considered. It should be noted here that the power will be generated in three distinct phases from PV, Biomass, Wind resources or diesel sets in most situations. Other major elements like line segments and transformers can be consisted of both three phases and single phase. The layout of most power systems tends to change from three phases to single phase circuitry at the extreme point of usage [12]. Thus, most systems will be a combination of three phase and single phase circuitry and equipment.

As line segments or transformers can be a part of three phase system, these can be configured in either star (also known as wye) or delta layouts. In traditional grid networks of main land, most common practice is to deploy a combination of star and delta connected equipments with power transmission in three phase delta and distribution in star connected. Change from delta to star and vice versa takes place in transformers. A single phase load can be connected between any two phases in a delta or a star system. Also it is possible to connect the load between one phase and the neutral in a star system configuration. In fact most of the domestic loads will suite this type of connection. While delta is the preferred style for high or medium voltage transmission lines or when power transmission cost is a major concern, star connected design is more preferred for distribution. Star configuration results in lower overall cost and increase in service reliability. Exactly how and where the transition from three phase to single phase circuitry takes place in a distribution system depends on several factors and no single hard and fast rule exists on this.

Wills [12] has reported that more than 80% of all distribution worldwide is accomplished using radial feeder systems, in which there is only one path between any customer and the substation. In majority of the cases the feeder system is physically constructed as a network (many paths from many sources), but is operated radially by opening switches at strategic points to impose a radial flow pattern. However, in the case of rural electrification in remote islands most of the cases radial feeders are designed and built as fixed radial circuits. For example, in Sundarbans islands region all distribution lines are fixed radial only. Radial system involves low cost and simplicity in operation and analysis. The major drawback of this system is in the lack of reliability which is often being compromised with the advantage it creates in remote locations. Feeder systems have a negative economy of scale – the bigger the area they have to serve the higher would be the cost per kW. As the load density increases, the overall cost per kW served usually tend to decrease, the spacing between substations will decrease and the capacity of the substations will increase.

2.3.2 Common Layouts

The common practice of any power distribution system is to provide three phase service to large loads like an industry or big commercial units. While in domestic usage where the loads are small as in developing countries the service will be single phase. In this regard most common three types of system layouts are briefly described below [12]

- **European layout** – here there are very few or no usage of laterals or single phase primary circuit elements. Service transformers are large and commonly configured in three phases as in the secondary circuits. End use customers are provided with single phase or three phase service from three phase secondary circuit. The circles in the figure 2.1 are the service transformers.

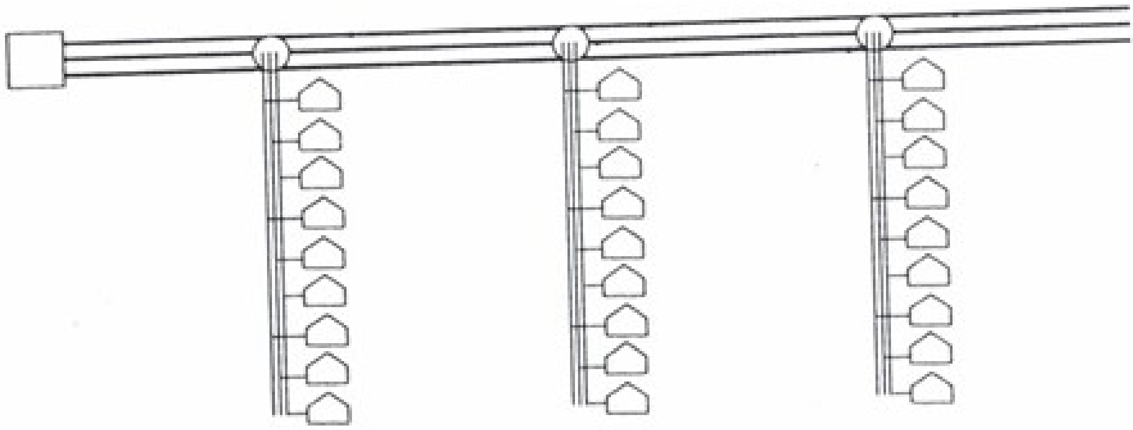

Figure 2.1: European layout [12]

- **American layout** – this system layout involves usage of single phase laterals and relatively smaller single phase service transformers. Relatively low voltage (120 volt) service level lines provide the same single phase of service to all customers in the immediate vicinity of each transformer. In the figure 2.2 the service transformers are represented by 9 small circles, 3 transformers from each phase.

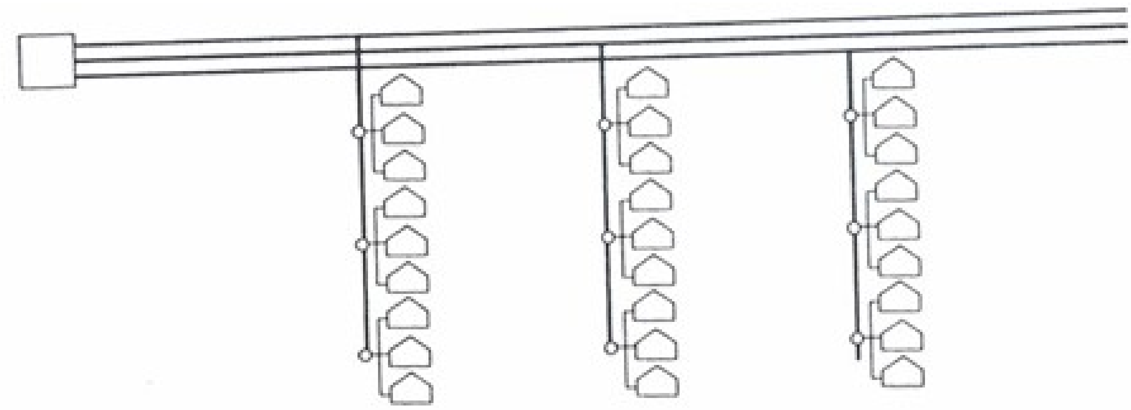

Figure 2.2: American layout [12]

- **Single phase earth return** – here the earth is used as the return conductor. Only one conductor, the phase wire, need be run in laterals to provide single phase service.

Single phase earth return system is very rarely used in practice. The usage of this system is limited to very sparsely populated regions. This is perhaps the cheapest system. This kind of distribution system with primary voltage of 66 kV and single phase primary feeder runs exceeding 120 miles has been used in some remote places in Canada, India and China [12].

The main benefit of the American system is that it involves low capital cost when the load density is low. European system is quite appropriate for higher load density like in the urban region. Because of the difference in service voltage (250 volts European and 120 volts American) European circuits can reach four times as far given any equivalent load and voltage drop limitation [12]. Also, a balanced three phase circuit can reach twice as far as a single phase circuit. In effect, Wills [12] stated that European systems do not need primary voltage laterals – the secondary can carry roughly eight times the burden, replacing the role of laterals in the American system. It should be clearly noted here that there exist areas with European systems of three phase secondary service in urban parts of America. Similarly single phase American distribution systems are also available in some portion of European rural region and street lights in some urban systems.

Power distribution in areas with low load densities has an overall cost per kW that is much higher than that for regions of higher load density. Therefore the rural distribution systems generally tend to compromise on the design standards and service criteria in comparison with urban or suburban systems. The design philosophy of a rural distribution system is dominated by voltage drop considerations that include the expenses of upgrading conductor size for lower voltage drop or installing voltage regulation measures etc. Wills [12] noted that usually the optimal primary voltage for rural application will be the lowest that can handle the load density without major amounts of conductor upgrade in order to have lower voltage drop at peak demand. Even smallest size line type is very lightly loaded compared to its most economic capacity, even at peak conditions, so much so that it results in much lower voltage drop (corresponding longer reach) than would normally be the case. Obviously at higher load densities higher voltage level is required.

2.3.3 Critical Distance for Grid Extension

It is relevant here to briefly touch upon the concept of critical distance for grid extension. The decentralized electricity generation option cannot compete with grid extension option, in terms of delivered cost of electricity, for villages that require grid extension from the existing electricity distribution network by a distance below a certain critical value. The decentralized electricity generation options become financially competitive only beyond this critical value of distance. Nouni et al. [13] had shown that for a fixed value of peak load and particular value of delivered cost of electricity from decentralized generation option, the value of the critical distance of grid extension increases with increase in the load factor. In the analysis for India they have demonstrated that "for smaller values of peak loads and low load factors the critical distance is rather small thus implying that in such situations the renewable energy based decentralized electricity generation options may be financially attractive to grid extension option even if the required distance of grid extension is small [13]." Thirault et al. [10] had developed and analyzed several scenarios in terms of variable distance of grid extension, distribution layout type, cost of fossil fuel, cost of electricity, number of households in a village etc. to find out optimal strategy for power supply and concluded that for all cases in his study single phase distribution system seemed to be advantageous over three phase one. They calculated for their cases that for an electricity cost of 0.038 Euro/kWh the critical distance come out to be 4 km for a village of 200 households and 13 km for a village of 1500 households. Beyond these distances the feasibility of extending MV grid does not work well in this case and decentralized generation option seemed to be more viable.

2.3.4 Principal technological configurations for autonomous hybrid systems

In the small islands of developing countries, electrification through renewable energy resources very often calls for the autonomous power supply system. For such systems in hybrid mode concerning PV, small Wind, small hydro, biomass, diesel generator etc. very often there is usage of inverters and battery bank storage. In this context the principal three system configurations are briefly discussed here.

System Type 1: Electricity generation coupled at DC bus

All electricity generating components are connected to a DC bus line from which the battery is charged. AC generating components need an AC/DC converter. The battery, controlled and protected from over charge and discharge by a charge controller, then supplies power to the DC loads in response to the demand. AC loads can be optionally supplied by an inverter. However, there exists one variation in the form of centralised DC bus concept for large installations. All generators are coupled on a DC bus while central power conditioning units(s) feeding the AC user loads. Usually, at each moment, only one grid-forming unit is connected to the user grid, while other units can act as current sources.

System Type 2: Electricity generation coupled at AC bus

All electricity generating components are connected to an AC bus line. AC generating components may be directly connected to the AC bus line or may need a AC/AC converter to enable stable coupling of the components. In both options, a bidirectional master inverter controls the energy supply for the AC loads and the battery charging. DC loads can be optionally supplied by the battery. Very common form is a distributed generators scenario. Distributed systems are feeding the user grid from multiple points and all the generators are coupled directly via the distribution grid.

System Type 3: Electricity generation coupled at DC/AC bus

DC and AC electricity generating components are connected at both sides of a master inverter, which controls the energy supply of the AC loads. DC loads can be optionally supplied by the battery. On the AC bus line, AC generating components may be directly connected to the AC bus line or may need a AC/AC converter to enable stable coupling of the components.

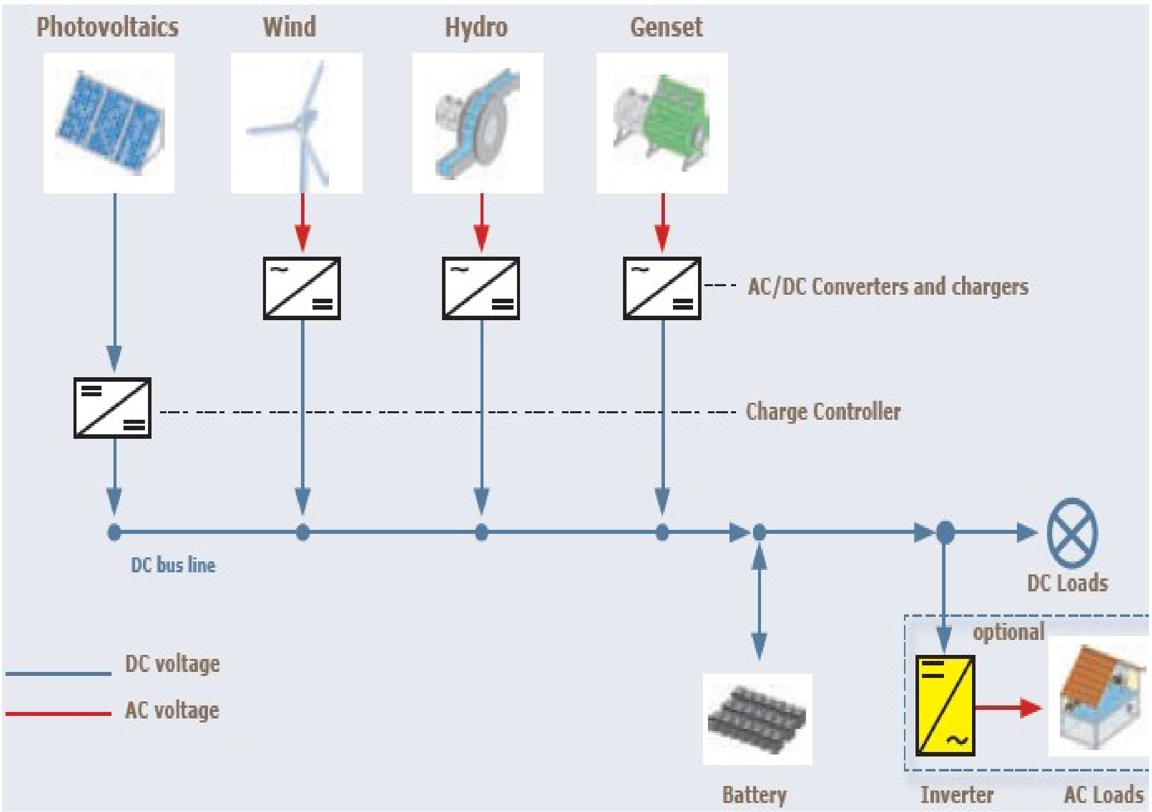

Fig 2.3: DC coupled system (source: [14])

All of these three configurations have relative advantages and disadvantages with respect to the technical as well as economic performance. Depending on the specific need and situation one out of these three types has to be deployed. The detailed evaluation on this subject is beyond the scope of this study. However, a few basic comments are given below.

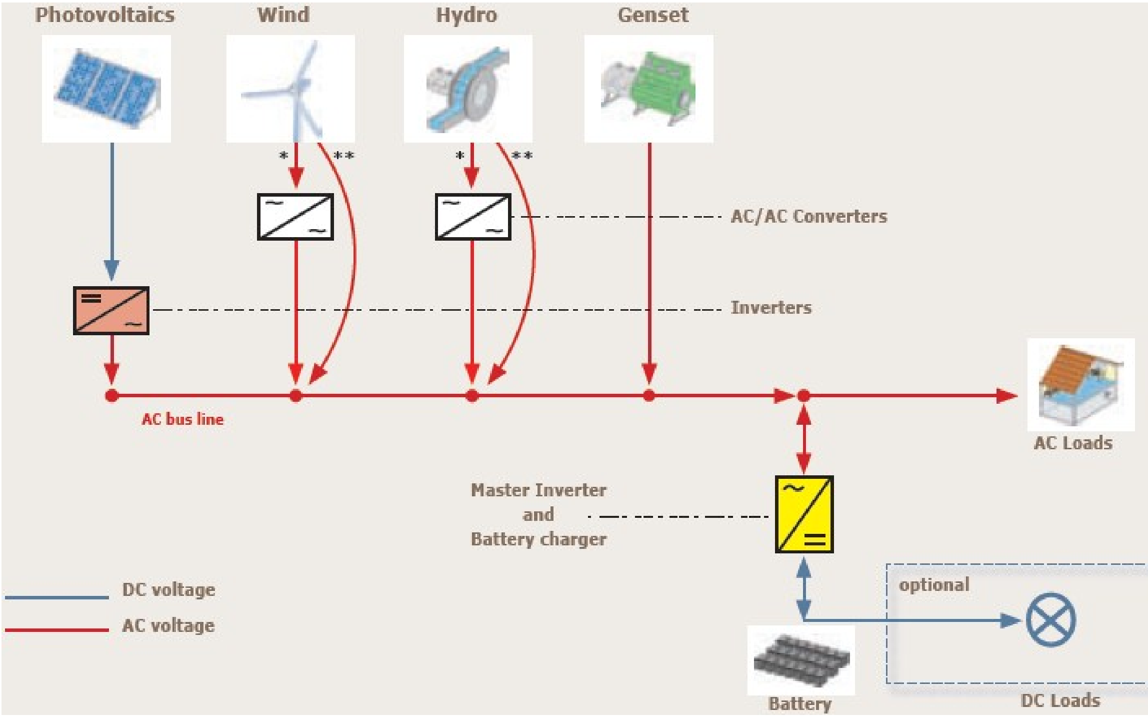

Fig 2.4: AC coupled system (source: [14])

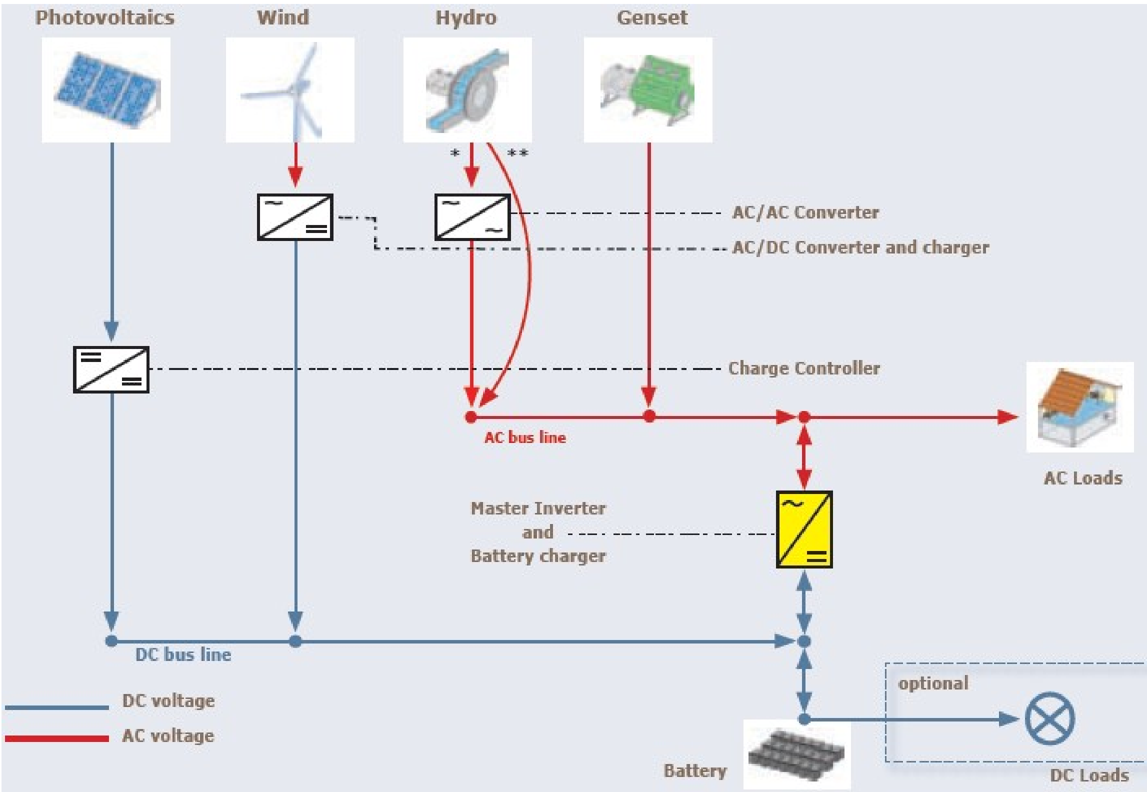

Fig 2.5: DC/AC coupled system (source: [14])

The main advantage of DC coupled central hybrid system is that they are robust and can be controlled more easily than the distributed systems. The communication among components is easy with relative shorter distances. On the other hand the basic advantages of distributed AC coupled systems are expansion capability, distribution line cost reduction, flexibility of generator location due to distributed nature etc. However, this system calls for much more sophisticated control and communication features [15]. The DC/AC combined type configuration has the minimum DC/AC or AC/DC conversion process leading automatically to advantageous position in terms of relative high efficiency [16]. Comparison of Type 1 and Type 2 has been reported by Gabler et al. [17] and Vandenbergh et al. [15]. Gabler et al. concludes that performance ratio is slightly smaller in the AC coupled system. However, the AC coupled system is not far away in performance, solar fraction and auxiliary energy input from the DC coupled system. Whereas Vandenbergh et al. observes that for high solar fraction the DC coupled system is generally preferable, unless most of the energy is consumed during the daytime. For hybrid systems with a decreasing solar fraction the AC coupled system becomes more efficient compared to DC coupled ones. Also for productive type of loads the AC coupled systems become attractive. He recommends to use AC coupled system when auxiliary energy input (e.g. genset) energy share is high and when significant amount of energy usage takes place during the day time. Whereas DC coupled system is recommended to be used with a high PV share and with the evening load as the main usage. For remote settlements of the islands of developing countries, the basic requirements normally are lighting and entertainments, particularly in the evening. Therefore, usage of DC coupled systems and/or DC/AC coupled systems can be probable for PV applications.

2.4 Relevant Software Tools and Energy Models

For the present research, on the optimal usage of renewable energy for the electrification of small islands, two models one concerning with the renewable energy based electricity generation aspects (HOMER) and another about the generation-distribution combination (ViPOR) are extensively used in Chapter 5. The models are adequately described in their respective sections. The following discussions in the current section are of general in nature and aim to present a preliminary overview on the subject.

Models are convenient tools in situations where performing tests or experiments in real world are impractical or impossible. Some advantages of using computer models include the followings

- They are explicit, their assumptions are documented
- They compute the logical consequences of the modeller's assumptions
- Comprehensive and able to interrelate many factors simultaneously
- They compute fast resulting in savings of time

Energy models are simplified representations of real systems and useful as they depict immensely complicated systems. There exist several kinds of energy models developed for different specific purposes. Two basic types of models might be of interest to the theme of this research study viz. energy policy models and renewable energy designing models. Also, models related to distribution layouts are relevant here. Energy policy related models are commonly classified into four following types:

- Optimisation models like MARKAL, EFOM etc.
- Simulation models like ENPEP/BALANCE, ENERGY 20/20 etc.
- Accounting frameworks like LEAP, MEDEE, MESAP etc.
- Hybrid models like NEMS etc.

However, this particular work is restricted to designing a renewable energy based electrification solution in village (micro) level. Thus energy planning and policy related models are excluded from the scope of the thesis and renewable energy based plant designing aspects are considered in details.

Amongst the renewable energy (RE) related models, hybrid energy models attract most of the interest in the present thesis. Hybrid Renewable Energy Systems (HRES) comprise of more than one type of generator with at least one RE source. Temporal mismatching of RE resources with the energy demand creates hybrid systems attractive. Very often HRES incorporate the strengths of RE as well as conventional systems like reciprocating engines powered by fossil fuels or even biomass gasifier generated producer gas etc. In Fig. 2.6 an example of common HRES configuration is shown.

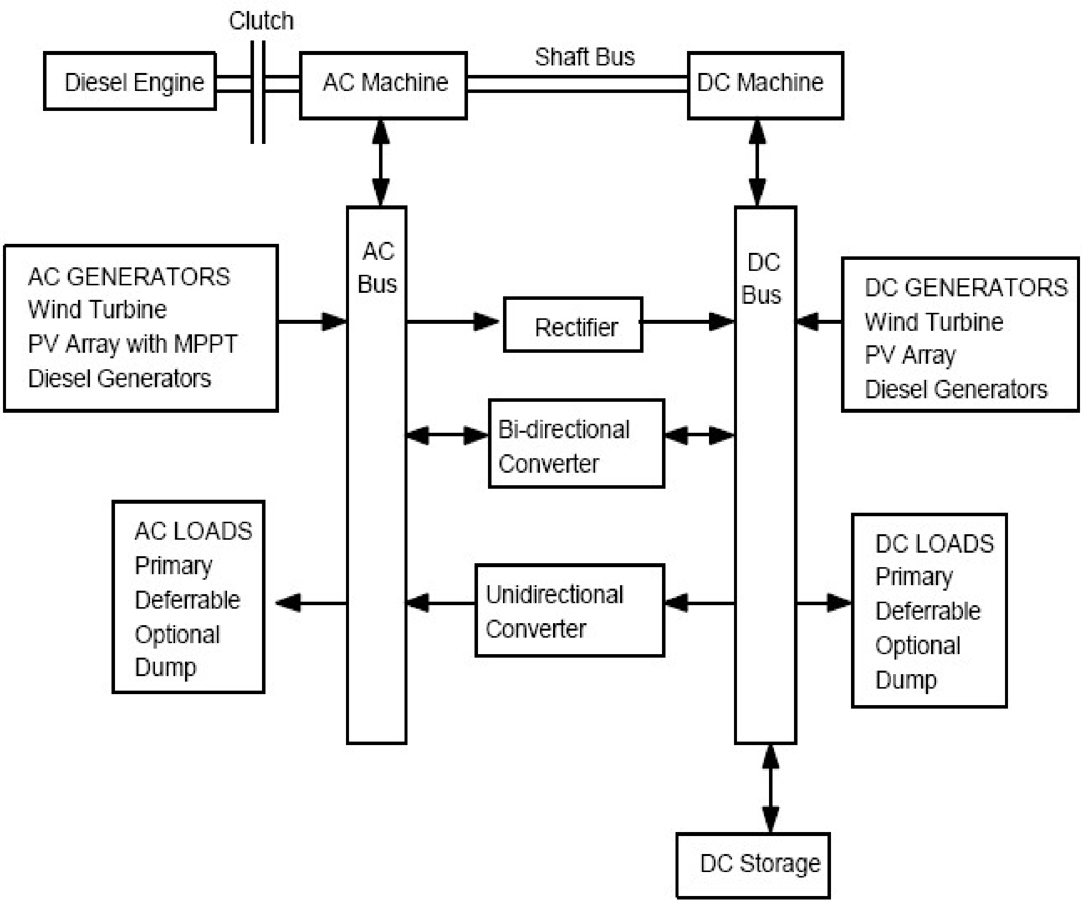

Fig 2.6: examples of common hybrid system configuration

Logistical (e.g. time series/probabilistic) and Dynamic (e.g. 1. Dynamic Mechanical, 2. Steady State Electrical, Dynamic Mechanical and 3. Dynamic Mechanical and Electrical Model) models are major categories of Hybrid RE models.

Several software dealing with HRES exist in the market. Some are commercial, some are free, some are developed within organizations exclusively for own usage. No single tool is best for all purposes and each model has its inherent accuracy and limitations. HOMER, Hybrid 2 and RETScreen are freely available models and all three are of Logistical in nature. These three models are quite popular. Each model relies on different modeling approach. HOMER and Hybrid 2 are time series models while RETScreen calculates the annual average energy flows. HOMER uses economic variables to optimize system design; Hybrid 2 is a performance simulator; RETScreen performs financial calculations. HOMER and Hybrid 2 are MS Windows applications and need no other software to run while RETScreen is MS Excel based spreadsheet model. In table 2.4 the modeling coverage is shown.

Table 2.4: Modelling coverage in HOMER, HYBRID 2, RETScreen

Characteristic	HOMER	Hybrid2	RETScreen
Hybrid Systems	√	√	
Optimization	√		
Sensitivity analysis	√		
Mainly Technical or Economical	Economical	Technical	Economical
Photovoltaics	√	√	√
Wind energy	√	√	√
Biomass	√		√
Biogas			
Geothermal			
Hydro	√		√
Diesel	√	√	
Cogeneration	√		
Microturbines	√		
Batteries	√	√	√
Fuel cells	√		
Electrolyzers	√		
Solar air heating			√
Solar water heating			√
Passive solar heating			√
Ground-source heat pump			√

HOMER and RETScreen are mainly economical while Hybrid 2 is mainly technical package. HOMER and Hybrid 2 are for hybrid systems, while RETScreen considers only single RE technology. Only HOMER includes optimization and sensitivity analysis capabilities. HOMER & Hybrid 2’s time step simulations are useful for understanding the time-dependent factors that affect system design. RETScreen’s simplified performance estimates are useful as the basis for financial calculations. HOMER’s simulation logic is less detailed than Hybrid 2 but more detailed than RETScreen. While considering time step analysis, in some instances, it may make sense to use HOMER to design an approximately optimal system, and then use Hybrid2 to refine the system design and further investigate its performance. In other instances, it may make sense to use only Hybrid2 or only HOMER. The internet websites of these three models are given below

- https://analysis.nrel.gov/homer for HOMER
- http://www.ceere.org/rerl/rerl_hybridpower.html for Hybrid 2
- http://www.retscreen.net for RETScreen

Advantages and weaknesses of HOMER

Main advantages

- Easy user interface
- Automatically finds the system configuration that can serve the load at lowest life cycle cost
- Can perform sensitivity analysis

Main disadvantages

- It is mainly economical model which is not a detailed model for system design
- Some RE technologies are not supported

Advantages and weaknesses of HYBRID 2

Main advantages

- It is mainly a detailed technical model dedicated to system design
- It has detailed dispatching options
- It tracks the changing voltage of the DC bus and its effect on the PV array, DC wind turbines and battery bank
- More accurate PV yield model

- It accounts for the fact that inverter efficiency is not constant
- It accounts for short term fluctuations of the load and resources that happen within the time step of simulation

Main disadvantages

- It does not have capability to perform optimization and sensitivity analysis
- Many RE technologies are not supported

Advantages and weaknesses of RETScreen

Main advantages

- It uses international product data from 1000 suppliers
- It uses international weather data from 1000 ground monitoring stations
- It evaluates GHG emissions reduction for various RETs

Main disadvantages

- It does not have capability to perform optimization and sensitivity analysis
- It cannot evaluate more than one RE
- Some RE technologies are not supported

HOMER gained tremendous popularity in last couple of years. In this thesis many important analysis were conducted with the help of HOMER as well. Therefore the basic features of HOMER are described below in more details.

HOMER

HOMER is a computer based simulation-optimization model developed by National Renewable Energy Laboratory, USA for evaluating design options for both off-grid and grid-connected micro power systems. HOMER models a micro power system's physical behaviour and its life cycle cost. HOMER allows the modeller to compare many different design options based on techno-economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs.

Principal tasks in HOMER

- *Simulation* – HOMER models the performance of a specific configuration time stepwise to determine its technical feasibility and life cycle cost. Simulation process determines whether a system is feasible and estimates the life cycle cost.

- *Optimization* – HOMER simulates many different configurations in search of the one which satisfies the technical constraints with lowest life cycle cost. Modeler has control over these parameters. Optimization process determines the optimal system configuration satisfying the user specified constraints at the lowest NPC (net present cost).

- *Sensitivity* – Multiple optimizations under a range of input assumptions to gauge the effects of changes over model inputs. Modeler has no control here.

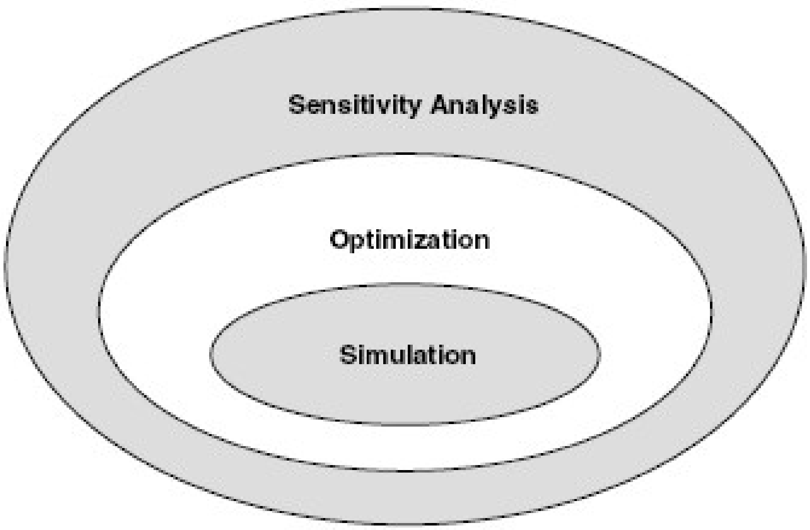

Fig 2.7: Principal tasks in HOMER

The main actions taken by HOMER are listed below

1. Energy balance calculations are normally performed on hourly basis and electric load for each of the hours is compared to the energy that the system can supply. Though now HOMER has the capability to deal with sub hourly time steps, if required.

2. For systems that include batteries or fuel-powered generators like biomass gasifiers, the software decides the strategy to operate generators and charging/ discharging of batteries.

3. Lifecycle cost is estimated taking into account the capital costs of various components /sub-systems, cost of replacements, operation and maintenance cost of the system, and the fuel and interest costs.

4. The software results in the least cost combination of components that meet electrical loads by simulating a large number of system configurations.

5. Lifecycle costs are optimized and the results of sensitivity analyses are generated.

6. A list of feasible systems, sorted by NPC and levelized cost of energy, is displayed after the simulation.

It should be noted here that a decision variable is a variable over which system designer has control and for which HOMER can consider multiple possible values in its optimization process. Common decision variables in HOMER include

- The size of PV array
- The number of wind turbines
- The size of each generators
- The number of batteries [18]
- The size of power converter
- The dispatch strategy

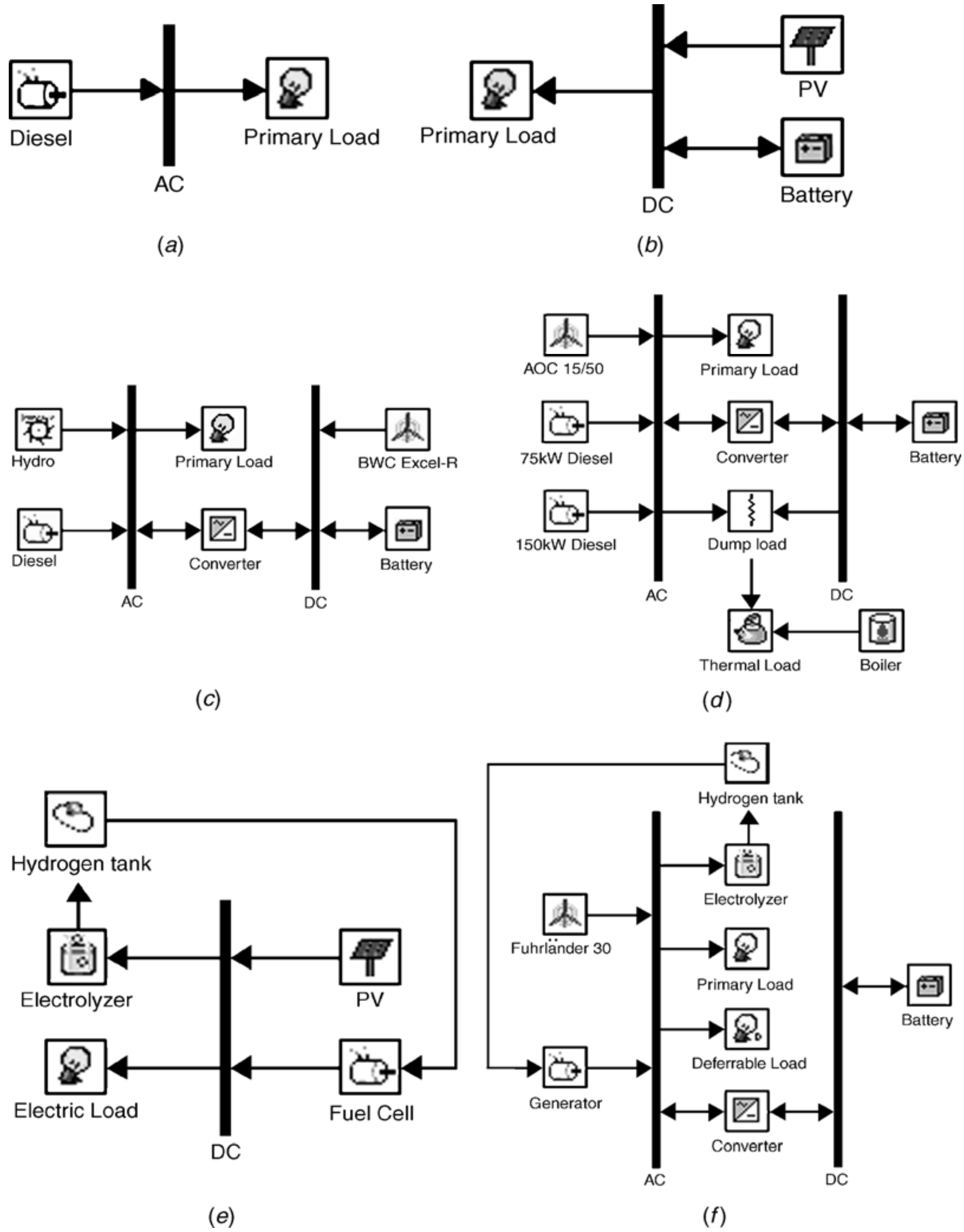

Fig 2.8: Examples of typical HOMER model types (contd. in next page)

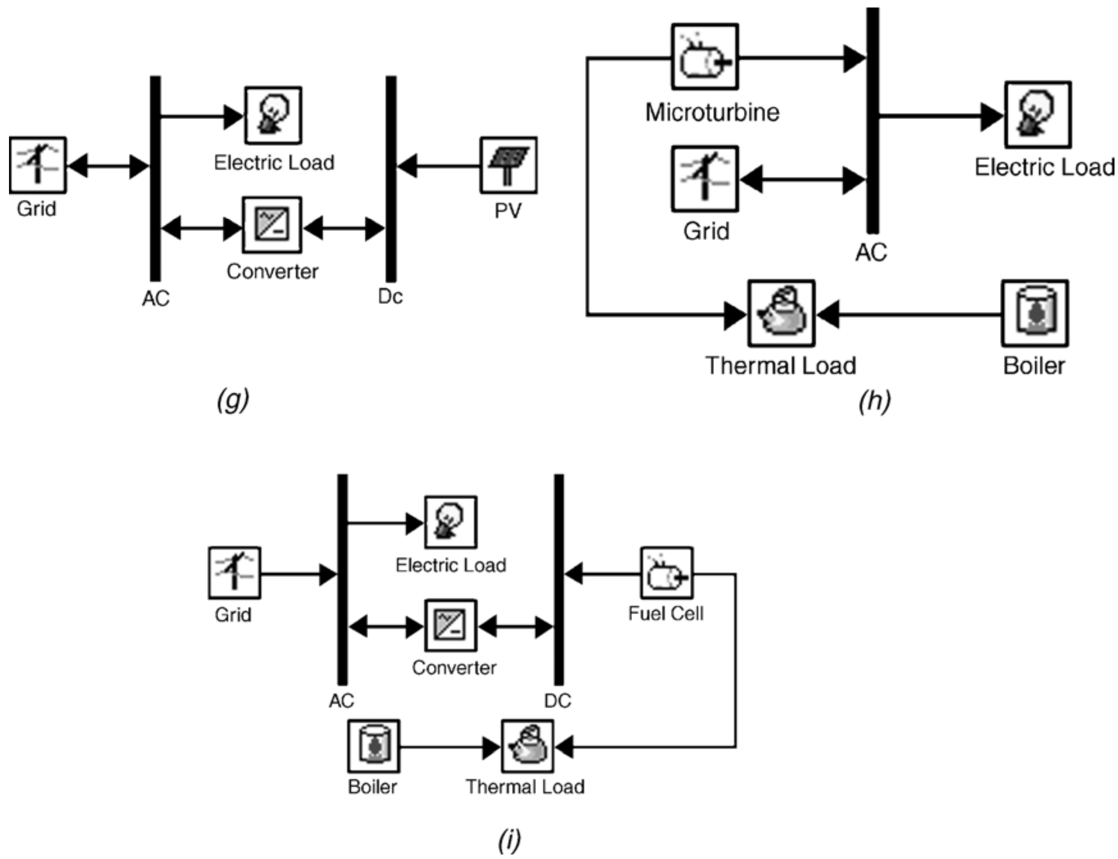

Fig 2.8: Examples of typical HOMER model types (contd. from last page)

Optimization task in HOMER helps the modeler to find the optimal system configuration out of many possibilities. A few important aspects are highlighted below

- HOMER assumes that both dispatchable and non-dispatchable power sources provide operating capacity
- HOMER does not attempt to ascertain the amount of operating reserve
- HOMER searches for the combination of dispatchable sources that can serve the electrical load, thermal load, operating reserve at the lowest cost

- HOMER assumes that all prices escalate at the same rate over project lifetime
- All costs in HOMER are real (inflation adjusted) costs
- HOMER uses NPC to represent life cycle cost of a system

ViPOR

As stated in the very beginning of this section another model called ViPOR is used extensively in the next chapter. Here salient features are highlighted very briefly.

Basic task

ViPOR is an optimization model for designing village electrification systems. Given an adequate map of a village and some information about load sizes and equipment costs, ViPOR decides which houses should be powered by isolated power systems (like solar home systems) and which should be included in a centralized distribution grid. The distribution grid is optimally designed with consideration of local terrain. ViPOR represents the village as a set of demand points, each of which consists of x and y coordinates and an average daily electrical usage. Several economic parameters are required to calculate the costs of the distribution grid and the isolated systems. Centralized generation costs are calculated using HOMER, which has been integrated into ViPOR. The planned location (or several potential locations) of the centralized electrical power plant can also be specified. With such data, ViPOR conceptualizes the lowest cost system that will supply power to each demand point-either with an isolated power source (such as a small wind turbine or a solar home system) or through a centralized distribution grid or a combination of these two. The design of the distribution grid involves the selection of the optimum location for the centralized power plant, the placement of multiple transformers, and the creation of a radial network of medium and low voltage lines. The voltage drop constraint is implemented using a maximum low-voltage line length, which limits the length of wire separating a demand point from its supplying transformer. ViPOR is not developed to be used for exact detailed technical designing of distribution system. It has broader range of applications in planning for an electrification project.

Optimization philosophy

ViPOR uses an optimization algorithm called simulated annealing to design the least-cost distribution system. Simulated annealing works by repeatedly making random changes to a system, allowing it to evolve towards the optimum. For example, ViPOR may randomly add a node to the distribution grid, move a transformer, or select a different centralized system location. Any change that results in a lower total cost (called a downhill move) is accepted and the system is allowed to continue to evolve from that point. However, changes that result in a higher total cost (uphill moves) are treated probabilistically: some are accepted and some are rejected. If a change is rejected, the system is returned to its previous state and another change is attempted. In the early stages of the solution process, the algorithm is very tolerant of uphill moves, but as the process continues, it becomes less and less tolerant of uphill moves. It is this feature of the simulated algorithm that allows it to search out the global optimum without getting caught in local optima. ViPOR performs its optimization procedure in two stages. In the first stage, a simplified algorithm is used to design the low voltage distribution system. This allows ViPOR to quickly determine the approximate number and location of transformers. In the second stage, a more sophisticated but slower algorithm is used to more accurately design the low voltage distribution system.

Simulation or/and design software tool: Simulation, optimisation tool

Programming Language: 32-bit Windows application written using Microsoft Visual C++

Source code available: No

Programmable or fixed system layout: Programmable

Which system components are included?

- All components of HOMER concerning power generation to use as input in VIPOR viz.

    1. PV

2. diesel generator
3. wind turbine
4. hydro turbine
5. battery
6. converter
7. electrolyser
8. hydrogen tank
9. reformer
10. hybrid electric vehicle
11. other types of generator

- Distribution line data for LV and MV systems
- Transformer data
- Load demand data for all load points
- Geographic information on load points, energy source points and terrain which influence distribution line layout

It is possible to create new components/models? Not possible to create new type of components. But within a certain available type its possible to create or use new products. For example it is possible to create various different wind turbines or battery banks.

The maximum low voltage line length: This input restricts the length of low voltage wire runs. It refers to the length of wire between a load point and the transformer to which it is connected, not the straight-line distance between the two. ViPOR does not calculate the voltage drops over the distribution lines

Price models included: Yes, the output gives cost of energy supplied

Lifetime models included: Yes, the calculation is based on levelized cost of energy and total net present cost

Graphic user interface input: yes

Graphic user interface for output: yes

Meteorological data base included, which continents: No

Load generator: Yes. One can give input to load demand by importing hourly values from a file or by manually feeding. It is also possible to add noise to the load profile in hourly as well as daily basis resulting in synthetic load data generation.

Average computing time for simulation: HOMER simulates on hourly basis for 8760 hours (1 year) [HOMER version 2.2 beta (October 2005)]. The more recent version of HOMER can simulate in 1 minute temporal resolution. ViPOR is not time series model.

Price: Free but need to renew license after each 180 days

Distributor: NREL, USA

http://analysis.nrel.gov/ViPOR/

Major Limitations of ViPOR: Key weaknesses are listed below

- It does not compute the voltage drops. Therefore load flow situations cannot be simulated by ViPOR. The maximum low voltage line length is the principal assumption used as an input parameter in order to avoid calculating electrical properties. ViPOR produces a rudimentary power system instead of rigorous one.
- It only considers radial system of distribution layout.
- It considers identical transformers for the entire power system
- It can not account for the change of line length due to the elevation of earth surface e.g. a hill slope.

Special comment: While using ViPOR within the tasks of the current research study it was felt that geographical data collection and handling as input to ViPOR need special effort and this is a potential area of spending substantial amount of time.

General Software for power systems modelling

Over the years various large scale power system simulation software packages have emerged. Power system analysis and design capabilities of these enable opportunities to work on more realistic problems. Some of the well known packages are Power Factory, EMTP, ETAP, NEPLAN, Elektra, SINCAL, Integral, EDSA, POWERWORLD, Cyme, etc. Figure 2.9 shows a general structure of these software.

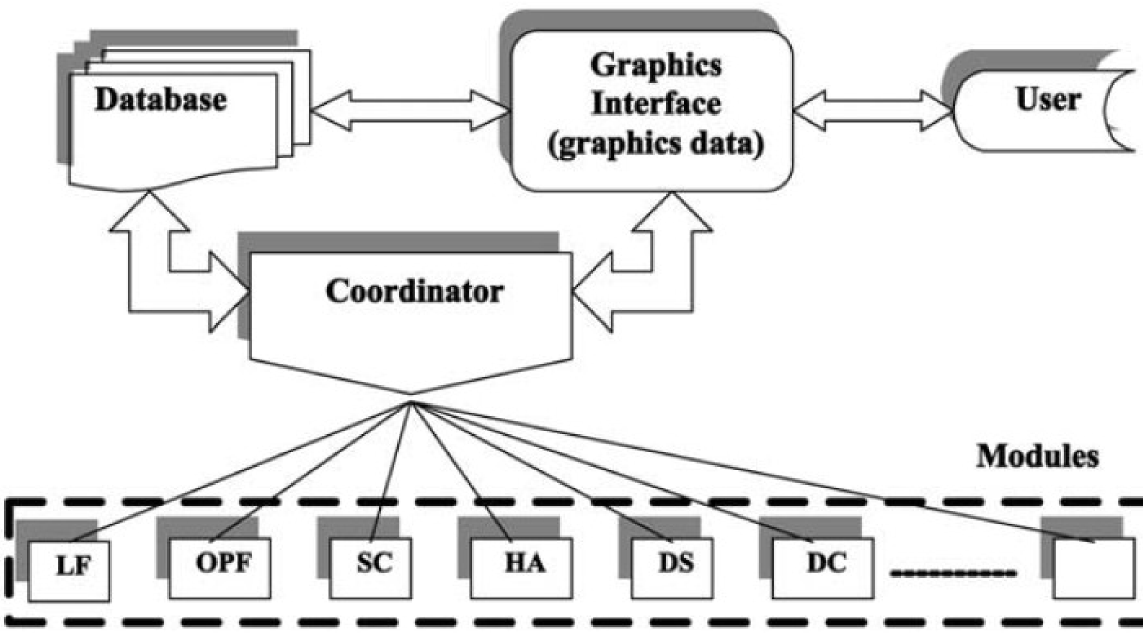

Fig 2.9: General structure of power engineering interactive software (source: [19])

Graphics interface, database and coordinator form the essential parts. There can be several modules and the exact kinds of modules vary with the specific packages. Load flow, optimal power flow, short circuit analysis, harmonic analysis, and dynamic simulation modules are quite popular among many possibilities. Ibrahim et al. [19] has conducted a comparative review of 13 most widely used packages with respect to their major modules, modelling capabilities, software and hardware requirements etc. His major conclusion is that no one package is suitable for all application needs. It seems till now no general software packages power systems like those listed before have capability to deal with Greenfield planning and autonomous power systems with renewable energy based units as power generators.

2.5 A Short review on spatial information usage for RE based rural electrification projects

The use of Remote Sensing (RS) and Geographic Information System (GIS) in energy studies has been widely acknowledged and numerous studies have been conducted towards the demonstration of the capabilities of spatial data in energy research and decision-making. Remotely sensed data offers viable solutions for different aspects in the life cycle of energy planning such as strategic planning, demand forecasting, economic analysis, feasibility studies, resource assessment, data dissemination etc. GIS based approach can help identify options for a given locality, village or town in terms of the technical and economic viability for grid extension or decentralized rural electrification.

Sustainable development of remote islands is often challenged by virtue of their low accessibility options. The difficulties in organising field studies often become a barrier for smooth progress in preliminary analysis level. Remote sensing thus can play a vital role in information generation and acts as a source of adequate baseline data for furthering strategies of electrification. The option of integration of remotely sensed data into a GIS offers the possibilities of strengthening the efficiency of the assignment. With advances in the integration of two major technologies - remote sensing and web GIS possibilities of minimizing the prohibitive costs of satellite imagery has emerged. Operability of internet based freely available high resolution satellite data needs to be explored for generation of preliminary research results. The present study has explored possibilities of conducting techno economic analysis through remote sensing and GIS for remote village electrification.

Remote sensing has been reported to be effectively utilised in numerous studies related to energy. The most common use of remotely sensed data has been towards the assessment of resources of renewable energy. Numerous such studies have been conducted at many regions across the globe. As renewable energy resources vary considerably from one geographic location to another, optimal sitting of renewable energy systems requires knowledge of the specific resource characteristics like availability, magnitude, and variability at any given location. With the aid of GIS, an evaluation of multifarious renewable energy sources according to local real land uses is able to provide more-integrated and accurate decision-making information for policy-makers and investors according to Yue et al., 2006 [20]. The study, conducted in Taiwan focussed on application of GIS to the local survey of the potential of different forms of renewable energy in the area. Use of remote sensing data provides a scientific method of hydropower identification and assessment [21]. In this study by Dudhani et al., 2006 the use of IRS 1-D images was demonstrated for information extraction of water resources and site selection for small hydro power projects for hilly as well as mountainous regions of north eastern India. Ramachandra et al., 2007 [22] have used GIS to map renewable energy potential at sub-district levels in the southern Indian state of Karnataka.

A comprehensive overview on the remote sensing techniques for biomass production and assessment has been given by Das et al., 2007 [23]. Satellite based irradiance maps with a high spatial and temporal scale were derived in research conducted by Beyer et al., in 1995 [24] and in 1996 [25]. A prime example of remote sensing applications to solar radiation assessment is the development of the HELIOSAT method to derive surface solar irradiation from satellite images. Geostationary satellites such as METEOSAT provide the opportunity to derive information on solar irradiance for a large area at a temporal resolution of up to 30 min and a spatial resolution of up to 2.5 km [26]. Data from three satellite systems- METEOSAT, GOES and GSM were used for Europe, America and Asia respectively. A multi resolution decomposition methodology was developed for the structure analysis of irradiance maps. Within the European project Heliosat-3, a new type of solar irradiance scheme is developed [27]. This new type is based on radiative transfer models (RTM) using atmospheric parameter information retrieved from the Meteosat Second Generation (MSG) satellite (clouds, ozone, water vapour) and the ERS-2/ENVISAT satellites (aerosols, ozone). A further study in Morocco [28], has underlined the importance of GIS in solar power projects, "…..combining all that data with a geographic information system (GIS) and using this database as input for a detailed performance model, a systematic ranking of sites for a whole country is possible". One of the most attractive aspects of GIS is the availability of a spatial database and its interoperability with external databases; ability to be upgraded and updated with information and also the capabilities of Web GIS. Analyses may be performed in conjunction with other data sources as well as dedicated software used for electricity planning and management such as HOMER. NREL worked with the U.S. Agency for International Development and the United Nations Environment Program to jointly develop software that integrates the model with GIS-based resource mapping software [29]. NREL has a dedicated GIS unit. NREL's GIS team analyzes renewable energy resources to determine which energy technologies are viable solutions in the United States and inputs the data into a GIS [30]. In the framework of the project SWERA (Solar and Wind Energy Resource Assessment) various applications of spatial data on renewable energy have been processed for about 17 countries. "The core mission of the SWERA Programme was to provide online high quality renewable energy resource information at no cost to the user for countries and regions around the world. Renewable energy maps, atlases and assessments can be downloaded. Likewise, GIS and time series data along with the energy optimization tools needed to apply these data can be downloaded to facilitate renewable energy policy and investment" [31].

GIS based Decision Support Systems (DSS) were designed as early as 1998. Voivontas et al., 1998 [32] used a DSS to map available and technological potential of renewable energy and have specifically studied wind power energy in the island of Crete. The GIS based DSS was developed on MapInfo platform. The study concluded that "GIS is a useful tool providing the means for identifying and quantifying the effects of local constraints on the RES potential. In addition, it provides the flexibility to enrich the database, on which decisions are based, with spatial data providing additional RES availability restrictions, or non-spatial data providing other technology alternatives". A Spatial Support System (SSS) has been developed by Monteiro et al., 2001 in Spain [33]. The SSS used GIS to compute spatial incremental costs on electric power distribution networks resulting from the integration of distributed resources. GIS for technology selection has also been developed by Govender et al., 2001 [34]. The study developed an

Electrification Planning Decision Support Tool for an area in South Africa which made it possible to automatically determine the members in a load polygon which are critical for further planning in electrification.

GIS has also been applied to facilitate electricity distribution as done in the study by Igbokwe et al., 2005 [35] in Nigeria. The study involved creation of a database of administrative locations and electricity supply chains to which queries were performed along with other GIS operations to arrive at a spatially explicit solution to the current status of electricity supply and future interventions possible for better distribution of electricity. The use of GIS for location based analysis towards the development of a power distribution system has also been substantiated in a study by Singh, R.P. et al., 2004 [36]. The study has conclusively outlined the efficacy of GIS based systems to identify locations for electricity distributions, complete information of consumers, calculate average annual distributed power and utilized power, load analysis and network analysis etc. Similar studies have been conducted in Uganda for assessing patterns of demand and prioritizing areas of investment. GIS can provide a key set of components needed for planning in the form of georeferenced data, using Global Positioning System (GPS) coordinates. In her study, Kakjuka, 2007 [37] has presented the demand side aspect of electricity planning. Demand sectors were targeted and provided a priority ranking through modelling in GIS for targeted electric supply. The role of GIS in distribution reforms has been examined by Raghav et al., 2006 [38]. They have found GIS to be useful in consumer indexing, load forecasting, load flow studies and Management Information Systems (MIS). GIS has been successfully implemented in meter installation surveys and distribution network modelling in the city of Roorkee in northern India.

Spatial costing models are useful tool for reaching technical and economic decisions in a territorial comparison of electrification alternatives [39]. Integrative analytical capacities of GIS are also used in decision making towards the best choice of the type of energy to be installed, which is one of the major challenges in rural electrification. Amador et al., 2005 [40] have used GIS to arrive at the most appropriate technology through a joint technical and economic analysis in terms of levelling electric cost. Another example of the utility of GIS in financial analysis in rural electrification is the study conducted by Luchmaya et al., 2001 in South

Africa [41]. GeoMedia Professional has been used to perform extensive terrain analysis to assess the cost of erecting cables for a specific type of terrain. An excellent example of GIS being used as part of an integrated planning tool for a grid connection assessment for prospective renewable energy generators is a study performed by Quinonez- Varela et al., 2007 [42] in Scotland. Analysis has been carried out by combining a commercially available GIS platform, IDRISI, with a standard PSS package for the planning process. Techno-economic assessment has also been carried out for a small island, Corsica, by Muselli et al., 1999 [43] using GIS to determine profitability boundaries for PV systems compared to a grid extension and under four different load profiles. The study has successfully formulated an integration plan for renewable energies for Corsica.

GIS offer a variety of structured data models suitable for the storage, manipulation, and analysis of the information needed in Distributed Generation (DG) planning [44].The application of GIS to DG can best be exemplified by the DISPOWER project which explored the potentialities of GIS as planning tools for DG and formulated guidelines for the use of GIS in DG operations. The usefulness of the technology and its capabilities of performing in accordance to the demands of the application has been summed up by the following excerpt from the DISPOWER Report 2003 –"Of course dedicated applications based on the capabilities of GIS in the framework of DG do not always exist, but GIS tools possess all the instruments to develop them." Under the framework of DISPOWER project, there were two case studies one in the island of Kythnos and the other in the "Les Saintes island of Guadeloupe archipelago, where GIS have been applied for technical analysis [45]. Bravo et al., 2007, [46] used GIS techniques extensively to analyse spatial distribution of renewable energy resources, to impose spatial restrictions related to land suitability (like land use, slope, productivity etc.) and to calculate capacity and generation ceilings based on available sites in Spanish peninsula. The results were both numerical and cartographical.

However, **this review also reflects certain gaps in the ground use of remote sensing and GIS for rural electrification**. **Majority of the studies have focussed on generating information on regional, national or global levels. The few studies conducted on local levels are characterized by regions**

where ample archival as well as administrative data on electricity supply and consumption are available. There is a gaping dearth of research initiatives on feasibility studies in remote areas that are limited by availability of secondary data and accessibility. **The review underlines the limited use of high resolution imagery for feasibility studies at explicitly local scales such as remote villages.** The current study enumerates an attempt for generating scenarios for electrification of a remote village in an island ecosystem under **the added stress of non existence of spatial** as well as documented secondary data through the use of high resolution remotely sensed image integrated into a GIS. The economic viability of the study is also high against the backdrop of having used freely available satellite imagery for the research. The key focus is to use the currently available tools in planning and management of electrification initiatives.

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Chapter 3

Distributed generation and microgrids for small island electrification in developing countries

There is increasing interest for worldwide deployment of distributed generation with a particular emphasis on the utilization of renewable energy resources. This is also relevant to the small islands in developing countries where the present need is to have access to adequate supply of electricity. This chapter reviews the concept of distributed generation, discusses its relevance in small islands, elaborates on the initiatives in the islands of Sundarbans region in India and reviews another concept called microgrid in light of the emerging technologies suitable for the small islands. An actual field test project in Kythnos Island, Greece has been concisely presented as an example of distributed generation and microgrids for island electrification.

3.1 Introduction

A trend is showing up internationally where more and more energy conversion units are located close to the consumers of energy and large units are partially replaced by smaller ones [1]. Much research and implementation have been accomplished in the area of distributed generation (DG). Interestingly, there exist several definitions of DG given by different authorities. The simple definition is provided by The European Commission as -"a source of electric power connected to the distribution network or the customer side" [2]. Power systems were originally developed in the form of local generation supplying local demand. Subsequent technology developments driven by economies of scale resulted in the development of large centralized grids connecting up entire regions and countries. In the last decade, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for distributed generation. In a broader outlook, distributed energy systems involve more than technological aspects of energy deployment. According to the World Bank, decentralization includes political, administrative, fiscal and market aspects [1]. However, most of the discussions in this chapter are restricted to technological features.

This chapter reviews the definitions and the characteristics of Distributed Generation. It outlines the situation of DG in India before describing DG initiatives and their benefits in the Sundarbans islands, which represent small island cluster in developing countries. An emerging distribution network control concept called Microgrid is also reviewed as an interesting approach for future transition from stand alone mini-grids towards interconnected systems with the main grid. An existing mini-grid in Kythnos Island, Greece is briefly presented as an example of island electrification with the help of advanced renewable energy technologies and application of microgrid concept. It is highly probable that the usage of such emerging technologies will increase in small islands of developing countries in the future.

3.2 Distributed Generation

A short survey and review was done to find out the definition of the term "Distributed Generation". This term is commonly perceived as small scale electricity generation. However, it seemed from the review that there is no consensus on a precise definition as the concept involves a broad range of technologies and applications in various different environments. As Pepermans et al. [3] describes, some countries define DG on the basis of voltage level while others follow a principle that DG is connected to circuits which feed consumer loads directly. Other countries define DG on the basis of some characteristics like using renewables, cogeneration, being non dispatched etc. The early definition is discussed by Ackermann et al. in 2001 with regard to the purpose, the location, the power scale, the power delivery, the technology, the environmental impact, the mode of operation, the ownership and the penetration level. His definition is "Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter. The distinction between distribution and transmission networks is based on the legal definition. The definition of DG does not define the rating of generation source, neither defines the area of power delivery, penetration level, the ownership, treatment within the network operation" [4]. IEEE has defined Distributed Resources (DR) as sources of electric power that are not directly connected to a bulk power transmission system. DR includes both generators and energy storage technologies. While the definition of DG is given as electric generation facilities connected to an Area Electric Power System (EPS) through a Point of Common Coupling (PCC) as a subset of DR [5]. EPS is defined as facilities that deliver electric power to a load; Local EPS as an EPS contained entirely within a single premises or group of premises and an Area EPS as an EPS that serves local EPSs. PCC is defined as the point where a local EPS is connected to an area EPS.

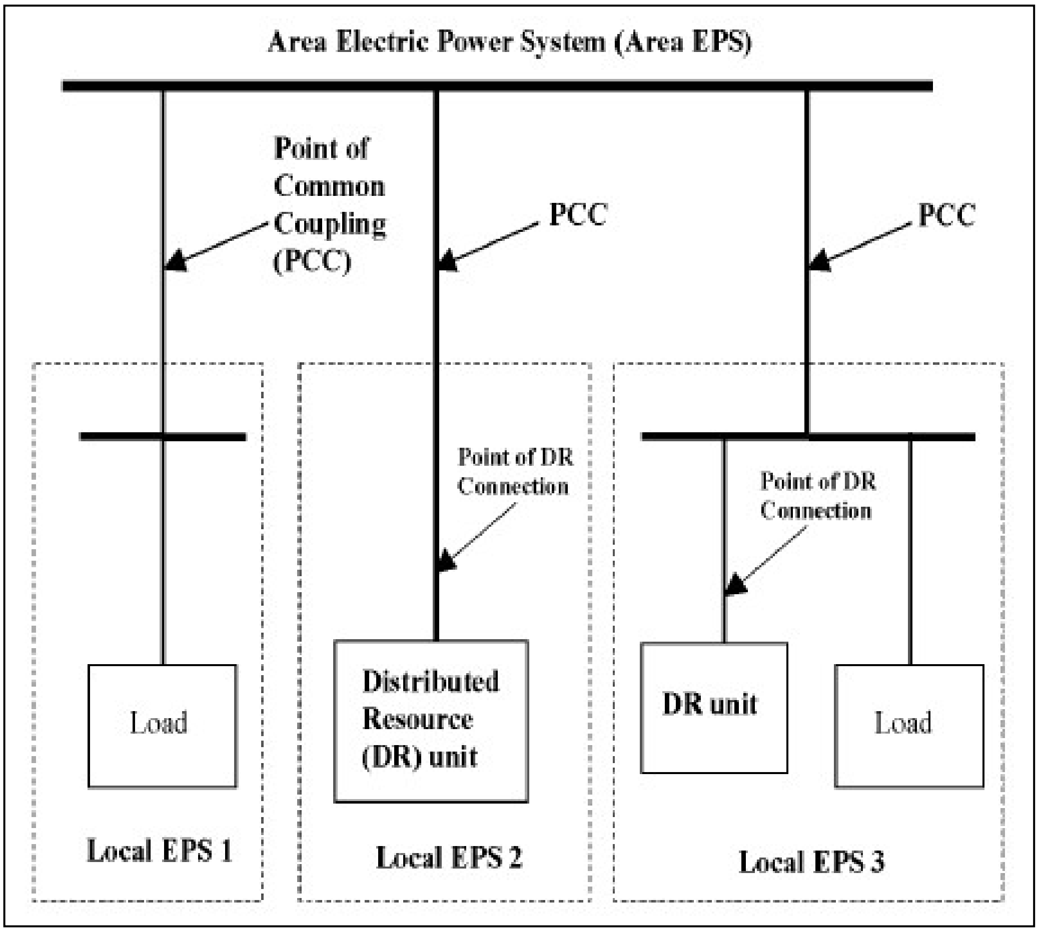


Figure 3.1: IEEE definition (Source [5])

International Council on large Electricity Systems (CIGRE) has a working group on DG who defined DG as all generation units with a maximum capacity of 100 MW that are usually connected to the distribution network and that are neither centrally planned nor dispatched [3]. IEA sees distributed generation as units producing power on a customer's site or within local distribution utilities, and supplying power directly to the local distribution network [6]. Willis et al. say -"DG, includes the application of small generators, typically ranging in capacity from 15 to 10,000 kW, scattered throughout a power system, to provide the electric power needed by electrical consumers. As ordinarily applied, the term distributed generation includes all use of small electric power generators, whether located on the utility system, at the site of a utility customer, or at an isolated site not connected to the power grid" [7].

DGs are usually classified according to their technologies (e.g. renewable or fossil fuel based), generated power type, supply duration, capacity etc. DGs are also categorised for specific applications they make in the electric system. Some of the most common applications for DGs [8] include standby, stand alone, rural and remote applications, peak load shaving, combined heat and power and base load. There are many terms referring to DG, such as 'dispersed generation', 'embedded generation', 'decentralised generation' and 'distributed decentralised generation'. In the International Electrotechnical Vocabulary (IEC 1/ 1999/CDV: 2006) the words 'embedded generation', 'distributed generation' and 'dispersed generation' have been defined together as generation of electric energy by sources which are connected in the power distribution system. Whereas the words 'small scale embedded generator' and 'micro generator' have been defined together as source of electric energy and all associated interface equipment able to be connected to a regular electric circuit in a low voltage electrical installation and designed to operate in parallel with a public low voltage distribution network [9]. Lambert et al. defined a 'micropower system' as a system "that generates electricity, and possibly heat, to serve a nearby load. Such a system may employ any combination of electrical generation and storage technologies and may be grid connected or autonomous" [10]. Pepermans et al. [3] reviews that many definitions suggest that at least the small scale generation units connected to the distribution grid are to be considered as part of distributed generation. Moreover, generation units installed close to the load or at the customer side of the meter are also commonly identified as distributed generation. He also argues that generation units should by definition at least supply active power in order to be considered as distributed generation. The supply of reactive power and or other ancillary services is possible and may represent an added value, but is not necessary.

The deployment of DG is growing worldwide. For example, the global off grid PV market is currently experiencing a growth rate of 20% per year [11], the cumulative capacity being 150 MWp in the year 2007. Many had described that micro-generation technologies have attracted increasing attention as potential future energy technologies [6], [12], [13]. Interest in micro-generation is also growing in government circles, with the UK Department for Trade and Industry (DTI) suggesting that by 2050 around 40–50% of UK energy needs could be met by micro-generation technologies [14]. Zahedi predicts that 'as alternative sources become more widely available, small-scale systems meeting local needs may start to replace central power stations' [15].

IEA [6] lists five major factors that contribute to the growth of DG, which are developments in distributed generation technologies, constraints on the construction of new transmission lines, increased customer demand for highly reliable electricity, the electricity market liberalisation and concerns about climate change. The great proportion of decentralised energy consists of high efficiency cogeneration systems in the industrial and district heating sector, fuelled by coal or gas, to a lesser extent, biomass based fuels [16].

3.3 Distributed Generation in India

Many countries have embarked on liberalization of their energy sector over the past two decades. These programmes with the objective to reduce costs and improve efficiency of energy services include privatization of the energy producers, separation between production and transmission activities, liberalization of energy markets, and lifting restrictions on capital flows in the sector. Overall, liberalization programmes aim at improving the efficiency of the energy sector, and should, therefore, lead to reduced emissions per unit of output. These initiatives, however, differ markedly from country to country. In this international backdrop let us look at the power situation in India. India had the fifth highest primary energy consumption in the world [17] and 3.5% of global commercial energy consumption in 2006. It is experiencing a steady growth rate of 6% per year in commercial energy consumption. As on 29 February 2008, the total installed capacity in the centralised electrical power utilities was 141499.84 MW [18]. Of this 64.50% was accounted for by thermal power plants, 25.00% by large hydro power plants and 2.91% by nuclear power plants. Renewable energy based electricity constituted 7.67% of the installed capacity (Fig. 3.2). Within the thermal power route, oil and natural gas based electricity generation capacity amounted to 11.10% of the total installed figure.

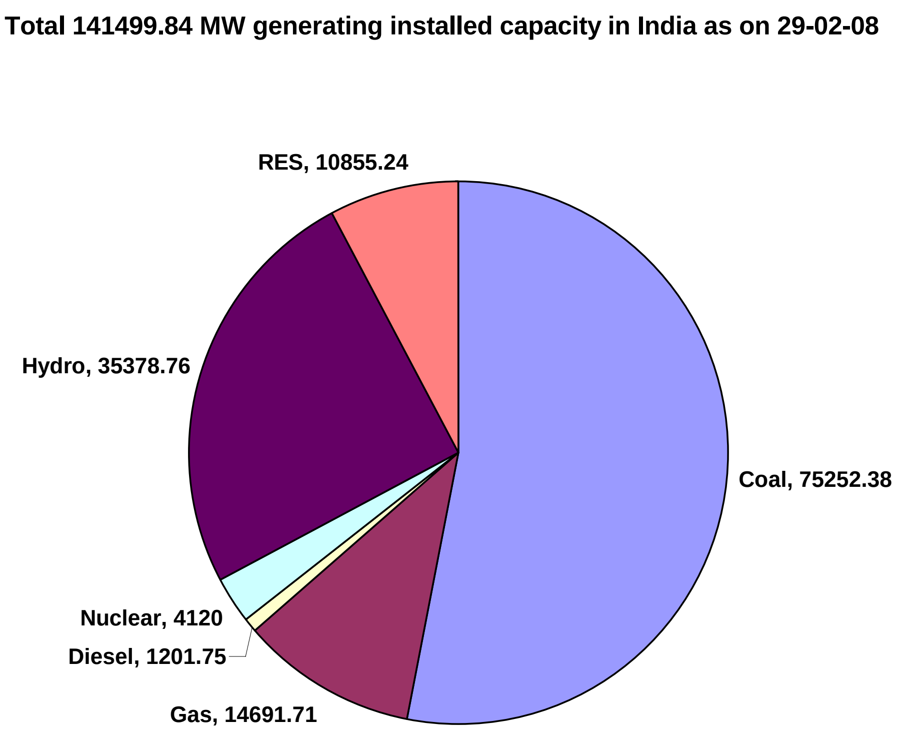


Figure 3.2: Installed generation capacity (MW) in India in the centralised utilities (source [18])

It should be noted here that India is increasingly a significant consumer of oil and natural gas in general and was the fifth largest consumer of oil in the world during 2006 [19]. India, as a fast developing economy, is facing increase in the energy and power demand - supply gap. The shortages in peak electricity demand (11650 MW) and energy supply (26793 million kWh) in the country during the period April-September 2006 were about 8% and 12.2% respectively [20]. India had a plan to add 100000 MW of additional power generation capacity by 2012. With centralised generating plants and centralised power grid only it is unlikely to fulfil this target since many settlements exist in widely dispersed rural areas. The country has a separate Ministry of New and Renewable Energy (MNRE) which promotes renewable based energy supply. Most of the installed capacity available from renewables is grid connected. Major contributors are small hydro, wind and biomass (cogeneration, combustion and gasification). MNRE has an ambitious target of meeting 10% of the power requirements from renewables by 2012. The reported installed capacity of DG in India is over 13,000MW (10,000MW diesel, 3000MW renewables).The majority of this is accounted for by diesel engines that are used for back-up power (in the event of grid failure) and operate at very low load factors. The share of the energy generation from DG is marginal (about 2%–3% of the total generation) [21]. In this background one fact is that out of total 586000 rural villages about 145000 are still not electrified. Out of total 138.27 million rural households 56.5% are waiting to be electrified in India [19]. India alone accounts for more than 35% of the world's population without electricity access, making it the largest contributor to the problem in the world [22]. There are several initiatives at present through different Government agencies to electrify remote Indian villages. The problems of high transmission and distribution losses; frequent disruption in supply of grid power; difficulties and financial concerns regarding extending power grid to remote areas; dispersed population in small villages resulting in low peak loads in rural and remote areas; poor financial health of the state electricity boards, etc. are reported as amongst the causes of barriers of rural electrification programmes in India. The national average T & D losses for 2004-2005 were about 32.5% [20]. Recognizing that electricity is one of the key drivers for rapid economic growth and poverty alleviation, the nation has set the target of providing access to all households in next five years [23]. The National Electricity Policy (NEP), 2005 aims at achieving a minimum consumption of 1 KWh/household/day by year 2012. In order to achieve this target, the policy calls for creation of a Rural Electricity Distribution Backbone (REDB) with at least one 33/11 kV (or 66/11 kV) substation in every administrative block and installing at least one distribution transformer in each village [22]. Electricity connection to households will be made available on demand. For achieving this target, wherever providing grid connectivity would not be cost efficient, decentralised electricity with local distribution would be considered. Both renewable based and non-renewable generation technologies will be taken into consideration. The relevance of decentralized form of power generation for remote villages has been recognised by a committee set up by the government [20]. NEP emphasizes that renewable energy based technologies would be considered even where grid connectivity exists, provided it creates cost-effectiveness. The Indian Electricity Act, 2003 provides the requisite framework for expediting electrification in rural areas with necessary empowerment. It permits operation of the stand-alone system in rural areas, independent of regulatory regime. It should be mentioned here that modern renewable energy resources and advanced technologies coupled with adequate storage systems compete favourably with conventional fossil fuel based power system, for the life cycle costs of the integrated energy system. This is true particularly when there are suitable renewable resources, a remote location and absence of interconnection possibilities with existing power grid [24].

While overall country is undergoing extensive capacity addition in electricity generation, transmission and distribution, Indian islands are mostly not properly electrified yet. Some of the bigger locations have diesel generators feeding to only a few kilometres of distribution line. India has a large number of remote small villages in the islands that lack access to adequate electricity, and probability of connecting them with the high voltage transmission networks in the near future is very less due to financial and technical constraints. The main electrical load in these villages is domestic in nature [25]. Though each island is different in its need for energy, they share some common characteristics regarding energy issues including heavy dependency of petroleum products, small scale generation of electricity, high distribution costs, under utilization of renewable energy resources compared to potential etc. Although islands produce only a tiny fraction of global greenhouse gas emissions they are among the most vulnerable to the effects of climate change. In this background, it should be noted here that renewable energy technologies are quite attractive for electrification of islands [26]. One example of deployment of DG in the islands of Sundarbans region is described in the following section.

3.4 Sundarbans Islands in India as example of DG deployment in islands

Sundarbans, world’s largest inter-tidal delta region containing vast areas of mangrove forests, lies between India and Bangladesh. Indian Sundarbans region is located between $21^{o}32'$ N – $22^{o}40'$ N and $88^{o}00'$ E - $89^{o}00'$ E. It is bound by the

Hooghly river in the west; Ichhamati, Kalindi, Raymangal rivers in the east; Dampire-Hedges line in the north and Bay of Bengal in the south. It encloses marshy islands covered with dense forests. Many rare and endangered species are present here, including tigers, aquatic mammals, birds and reptiles. This region has mainland as well as 102 deltaic islands out of which 54 are inhabited. The islands suffer from chronic shortage of electrical energy due to non availability of grid quality power [27]. Rivers are tidal in nature and sometimes become even 1 km wide. It is extremely difficult and very expensive to extend transmission lines from main land to these islands resulting in technical limitations and prohibitive cost. People depend on the expensive and often erratic supply of kerosene for their lighting needs. There are a few small diesel generator sets supplying electricity to the markets of some villages, but the diesel delivery mechanism is not reliable. There is absence of diesel based grid systems because the region has the characteristics of sensitive ecosystem, remoteness, inadequate infrastructure for transport sector, distributed demand for electricity and dependency on petroleum products imported from main land. There exists little or no reliable access to communication systems, television, and health facilities, all of which requires electricity [28] and [29]. West Bengal Renewable Energy Development Agency (WBREDA), in association with Ministry of New and Renewable Energy (MNRE), Government of India, has taken several initiatives since 1994 to meet the electrical energy needs for the people living in the islands. The key factors in determining the cost of grid extension, comprising installation of high or medium-voltage lines, substation(s) and a low-voltage distribution, are the size of the load to be electrified, the distance of the load from an existing transmission line, and the type of terrain to be crossed. Costs of electrifying small communities through grid extension are very high and therefore, not economically viable in many cases due to the lack of critical mass, the low potential electricity demand, and the, usually, long distances between the existing grid and the rural area. The lack of local technical and management personnel and the high transmission losses are also deterring factors playing against this solution. The electrification with renewable energy systems provides in this case a cheaper and less polluting alternative. The increased reliability of these systems, the insignificant power transmission losses, the potential consumer involvement (through an adequate operation scheme) and the optimal use of indigenous resources, play in favour of the decentralized solution [30]. Very often remote rural electrification options narrow down towards autonomous power systems with renewable energy based generation units [31]. Particularly for India, the decentralized style of electrification has also been found out to be the most suitable for remote regions [20]. In the case of Sundarbans islands, the electrification route was decided to be based on renewable energy entirely. So far over 50,000 households have been benefited by WBREDA's initiatives. Provision of electricity based on renewable resources to such a large number of households, previously not electrified, is a landmark effort towards sustainable development. Environmentally benign technologies harnessing solar, wind and biomass resources are serving over 283500 people to have benefits of access to electricity, as listed in Table 1. The emergence of electricity has led to significant changes in the society including economic growth, education, resource conservation, health and social status amongst many others [32] and [33]. Drinking water and health care provisions are enhanced. The use of renewable energy is also a major contributor towards preservation of the enormous biodiversity of the largest mangrove ecosystem inhabited by endangered species of flora and fauna. Institutional linkages with government have been strengthened and a pragmatic approach to the plights of the rural population has been adopted. However, there are about 106150 households that do not have access to electricity as yet. They are distributed in 131 remote villages in 20 islands [28].

Table 3.1: Renewable energy based electricity projects in Sundarbans from WBREDA as on Nov. 2007

Renewable Energy Project	Number	Aggregate Capacity	Benefited Households	Population Covered
Solar Power Plant	16	1005 kWp	5,010	26,720
Solar Home Lighting System	42,000	35 Wp to 74 Wp per system	42,000	240,000
Biomass Gasifier Power Plant	3	1400 kWe	1,800	10,800
Wind-Diesel-Gassifier Hybrid plant	1	740 kW	1,200	6,000
Total			50,010	283,520

Though the evolution of DG concept is linked to traditional grid connected distribution systems of developed countries, the above mentioned electrification initiatives in Sundarbans are examples of stand alone type DG deployment. Except small capacity solar home system units all other plants consisted of autonomous minigrids. Among these renewable energy based power systems all solar photovoltaic projects are having energy storage units in the form of lead acid batteries.

3.4.1 Drivers of DG in small islands of developing countries

Several examples are known on the remote islands of developing world where there exist no centralised distribution network system [29]. In those islands the main driver for deployment of DG is to provide access to electricity for people. However there exist various specific technical drivers, which include –

- Energy security – As Pepermans et al. [3] pointed out, the energy security is linked with (a) diversification of primary energy supply. It is also interpreted as (b) the reliability of the electricity system. Particularly in the places like Sundarbans islands where the potential consumers of electricity are located in remote areas, the usage of fossil fuels does not contribute to the energy security at all. On the contrary this remoteness creates a favourable situation in islands for using renewable energy based DG systems. DG deployment is less vulnerable to external risks. Situations such as wide spread electricity black outs will not occur in case of DG based electricity supply.

- Environment – This is in general one major driver for growth of DG world wide. For areas like Sundarbans avoidance of construction of new centralised power plants and transmission lines not only help in the environment but also helps in reducing the otherwise inevitable transmission and distribution cost. IEA 2002 says on-site production could result in cost savings in Transmission and Distribution of about 30% of electricity costs [6]. In general the smaller the customer size, the cost of transmission and distribution increases. This is of particular relevance to the remote locations like Sundarbans islands. In general DG involves no deteriorated landscape due to large power stations. On the other hand, from the point of fuel usage, smaller DG plants are generally less efficient than larger central plants of same size. In this context Pepermans et al argues that the key challenge is to design a framework that fully reflects the costs and benefits associated with DG to the economy and to the environment. From the point of view of limiting GHG emissions and climate change it can be said that the Governments promoting renewable energy will support renewable energy based DG deployment. Indeed, the aim to reduce emissions has been considered as one of the major influences for the changes towards the DG. Decrease in emission due to reduction of transmission losses is also one factor in favour of DG. Haeseldonckx et al. [34] concluded that the simultaneous, massive introduction of different decentralised generation technologies can significantly contribute to the necessary reduction in GHG emissions.

- Power quality – The presence of DG close to load centres can have a beneficial impact on power quality and supply reliability. In rural distribution systems the resistance in the distribution lines is considerably high. This causes significant voltage drop along the line. The introduction of DG can help in voltage profile improvements. However, this voltage rise effect is one factor that limits the number of DG units that can be connected to the distribution systems [35]. Islands like Sundarbans have stand alone distribution lines still now. But in the future if they will be gradually upgraded to form interconnected grid system then there would be several parameters of power quality which should be maintained and controlled carefully. Maintaining system frequency, voltage, harmonics and transient are some of them. And there may be requirements of special protection schemes associated.

3.4.2 Benefits

Alanne et al.[1] concluded that distributed energy system is a good option with respect to sustainable development in the long run. DG implementation in the distribution system of a typical remote and small island has many specific benefits. El-Khattam et al. [8] has listed several benefits of DG which includes some of them suitable for island electrification projects in developing countries.

- DGs can provide the required location flexibility in catering to load increases by installing them in certain locations. DG also has flexibility in terms of openness to different fuels and new technologies.

- They can be installed in a short period. They can be assembled in modular way. Each module can be operated immediately and separately. They are not affected by other modular operation failure. The total capacity can be increased or decreased by adding or removing more modules.

- With regard to environment and society, renewable based DGs eliminate or reduce the output process emission.

DGs can also be very effective when one island is already connected through distribution grid. DG can support and regulate the system voltage at rural applications connected to the grid. DGs can also reduce the distribution network power losses, distribution loads requirements by supplying some of the distribution load demand. DGs maintain system stability, supplying the spinning reserve required. DG s'capacities vary from micro to large size, so they can be installed on medium and / or low voltage distribution network. DG is capable of utilizing existing infrastructure. Thus, DG can be considered as adaptable to the future networks. Burton et al. [14] studied the social, economic and environmental advantages of small power generation vis a vis large centralised systems for a local case in UK. Their results indicated that small-scale approaches have more merit from a social and environmental perspective and that large-scale approaches are more economically viable given current cost structures. In terms of the overall social, economic and environmental cost, the results demonstrated that small-scale approaches are more effectual in their case study. Improved employment situation is possible through deployment of DG.

3.5 The Microgrid Concept

In developed countries' context, now-a-days active distribution network management is being thought for the key to effective integration of DG into the distribution operation and planning [35]. Traditional system of distribution network where the role is to receive bulk power from transmission and to supply to the end users at low voltage level, does not have much scope for DG to be added into the system. Whereas in contrast, active management techniques enable the distribution network operator to maximise the use of the existing circuits by taking full advantage of generator dispatch, control of transformer taps, voltage regulators, reactive power management and system reconfiguration in an integrated manner. Active management of distribution networks can improve the cost-efficiency and reliability by making use of ancillary services provided by DG [36]. Alanne et al. [1] argued that the best solution is likely to be an energy system that combines the benefits of both centralised as well as decentralised energy generation. Probably the future structure will consist of centralised and decentralised sub systems operating parallel to each other. In this changing scenario the emerging microgrid concept can be hoped for being in practise in the future physical island power systems as well.

3.5.1 Definition of Microgrid

One starting point for the idea of microgrid was a proposed concept with modular technology that can provide grid compatible PV power supply [37-39]. "Interconnection of small, modular generation to low voltage distribution systems forms a new type of power system, the microgrid. Microgrids can be connected to the main power network or be operated autonomously, similar to power systems of physical islands"- define Hatziargyriou et al. [40]. European Commission defines micro grids as small electrical distribution systems that connect multiple customers to multiple distributed sources of generation and storage [41]. It also commented that microgrids typically can provide power to communities up to 500 households in low voltage level. These clearly depict that it is suitable for electrification of small remote islands in developing countries. Early definition by Lasseter [42] implied the concept of microgrid as a cluster of loads and microsources operating as a single controllable system that provides power to its local area. This concept provides a new paradigm for defining the operation of distributed generation. It enables high penetration of DG without requiring re-design or re-engineering of the distribution system itself. During disturbances, the generation and corresponding loads can autonomously separate from the distribution system to isolate the microgrid's load from the disturbance without harming the transmission grid's integrity. Piagi et al. [43] argue that the intentional islanding of generation and loads has the potential to provide a higher local reliability than that provided by the power system as a whole. Microgrids can operate either interconnected to the main distribution grid, or even in isolated mode. From the grid's point of view microgrid can be operated within a power system as a single aggregated load and as a small source of power and other services supporting the network. A customer sees it as a low voltage distribution service with additional features like increase in local reliability, improvement of voltage and power quality, reduction of emissions, decrease in cost of energy supply etc.

Arulampalam et al. [44] has described a microgrid as a combination of generation sources, loads and energy storage, interfaced through fast acting power electronics. This combination of units is connected to the distribution network through a single point of common coupling (PCC) and appears to the power network as a single unit. A simple layout from his work is shown in Figure 3.3. Lasseter [42] argues that power electronics would be a crucial feature regarding microgrids since most of the microsources must be power electronically controlled to gain required system characteristics. Some of the key technical issues are power flow balancing, voltage control and behaviour during disconnection from the point of common coupling (islanding), protection and stability aspects. It is expected that microgrids will operate connected to the main grid under most conditions. When failures occur in the MV or HV system, the microgrid is automatically transferred to islanded operation, supplied by itself from the micro generators distributed with it, as in the physical island power systems.

3.5.2 Potential application for island electrification

It is quite evident that there can be enormous potential of microgrids for the electrification of small islands. The most immediate sites for application of the Microgrid concept would be existing remote systems which consist of a bundle of microsources and loads. It could be prohibitively expensive to compensate for load growth or poor power quality, by up rating the long supply line and the feeder to the (weak) source bus. Upgrading the local sub-system to a Microgrid could be a cheaper option [44].

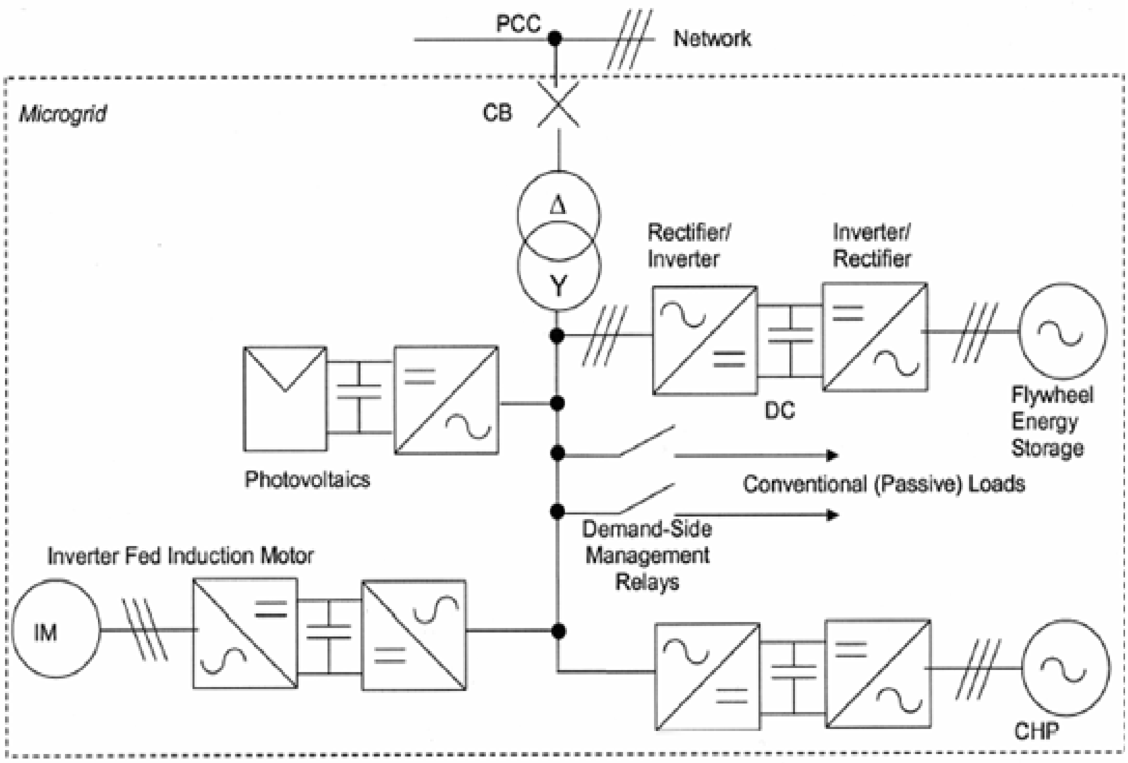


Figure 3.3: A simple microgrid (Source [44])

Another impression about the communities opting for the decentralised approach in a grid-connected area is that the communities will want to remain connected to the distribution grid that is fed by the central power system. This means that in those cases the central system acts as the back up for the decentralised configuration [34]. This is particularly in line with the development of microgrid philosophy. As microgrid is being developed for operating in grid-connected mode under normal operation, justification for configuring a system for microgrid is rather difficult in developed countries where high degree of reliability is presently being offered by power systems. The situation is more favourable to the remote islands of developing countries where the normal grid condition is weak and the power supply is less reliable. The role of microgrid will be certainly beneficial to the energy supply reliability concerns.

A concrete example of the potential deployment of DG in islands can be found in [28] where for the remaining not electrified settlements in Sundarbans islands, as mentioned in section 4 of this article, an extensive study was conducted. The study proposed 35 new renewable energy based hybrid power plants which can electrify 11275 households and 3200 shops spread over 20 islands. It should be noted here that this proposal for deployment of DG in the form of village scale mini-grids was developed considering the present level of techno-economic feasibility and policy prevailing over the specific region. These power stations can, in principle, be built to form several microgrids. A large of number of population would still remain not-electrified and would create further scope for DG and microgrid deployment in the future. Similarly there exists significantly high potential to build microgrids through out the islands of developing countries.

Arulampalam et al. [44] observe that there exist still a number of technical challenges in order to have a well behaved microgrid. This includes understanding of systems stability, protection, and unbalanced current compensation. The operation of micro sources in the microgrid introduces complexity in the low voltage level but at the same time, it can provide benefits to the overall system performance, especially regarding reliability and quality of service, if managed and coordinated properly. If a system disturbance causes a general blackout at the HV or MV networks, such that the microgrid is not able to separate and continue in islanding mode, and if the MV system is unable to restore operation in a specified time, the microgrid should provide local black start capabilities. A number of technical and regulatory issues are reported to have the need be solved before allowing such type of islanded operation. For example, in inverter-dominated microgrids, single-phase fault currents are typically very small posing problems to timely detection and protection.

Microgrid is still a new concept but research has reached the point of demonstration of practical operating systems. Both in Europe and in North America various scientific communities focus now on implementation of real systems. Till this time many issues and concepts were developed in simulated or controlled environment [45]. Research within the EU FP5 Project **MICROGRIDS** [46] focused on the operation of a single microgrid, has successfully investigated appropriate control techniques and demonstrated the feasibility of microgrids operation through laboratory experiments. The EU FP6 Project **MORE MICROGRIDS** [46] extends the work and aims at the increase of penetration of microgeneration in electrical networks through the exploitation and extension of the microgrids concept, involving the investigation of alternative microgenerator control strategies and alternative network designs, development of new tools for multi-microgrids management operation and standardisation of technical and commercial protocols.

3.6 Example of Kythnos Island mini-grid system

There is one field demonstration of stand alone DG in Greece which possesses some features of microgrid and it would be connected to the main grid in the near future. The system is electrifying 12 houses in a small valley in Kythnos, an island in the cluster of Cyclades situated in Aegean Sea. Figure 4 shows the mini-grid layout for the settlement that is situated about 4 kilometres far from the medium voltage grid line of the island. The Kythnos mini-grid consists of 10 kWp solar photovoltaic capacity distributed in five smaller sub systems, a battery bank of 53 kWh capacity and a diesel generator of 5 kVA nominal output power and three 4.5 kVA each battery inverters to form the single-phase grid. Each house has energy meter with 6A fuse, as per the norms of Public Power Corporation, the local electric utility. Specially developed load controllers were installed at every house.

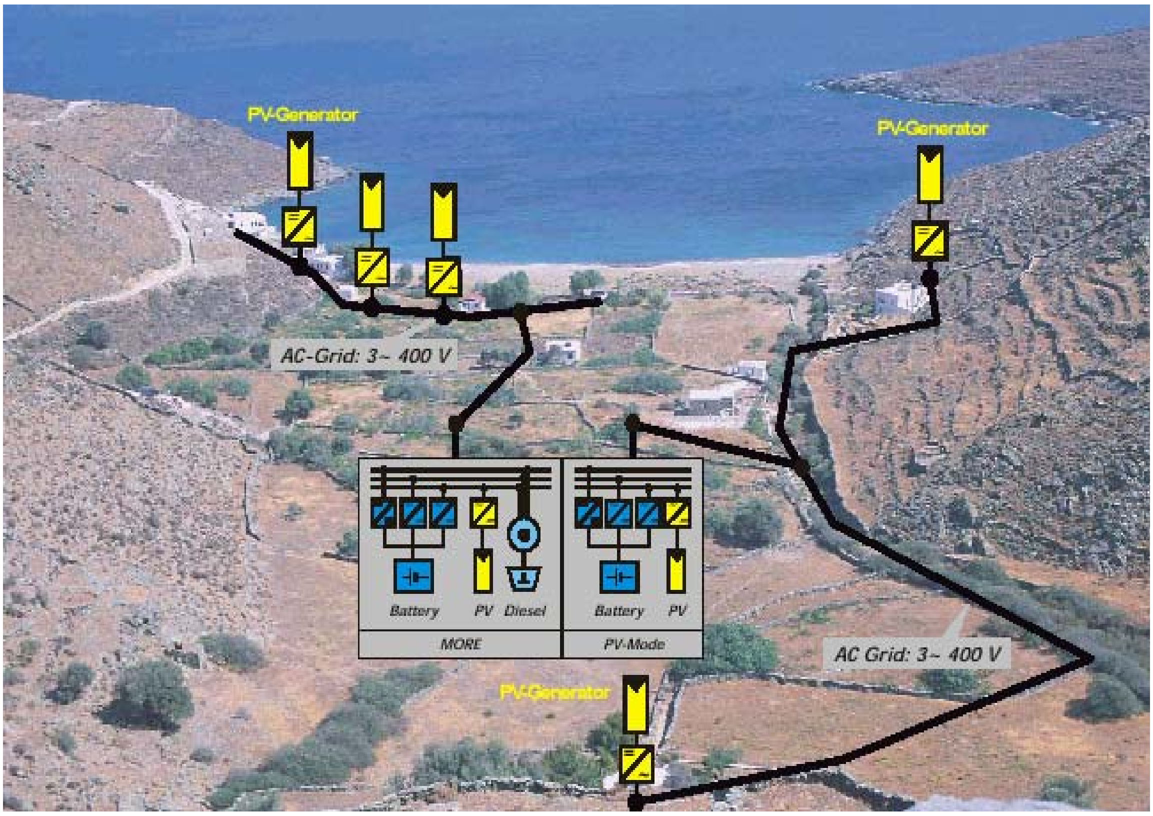


Figure 3.4: Kythnos Island project layout (source: [47])

The research institutes ISET e.V., Germany and CRES, Greece together with the company SMA Technologie AG, Germany formed the main partnership for this project. The systems were installed in 2001 in the framework of European projects PV-MODE and MORE [47]. They were co funded by the European Commission. Since then many changes, tests and demonstrations were conducted and are still going to explore various technological innovations. There exist a number of publications on this project and its technical components which include [39, 47-53]. The basic principle of the system layout is that three bi-directional battery inverters, Sunny Island 4500 from SMA, are forming the AC bus with the help of the energy stored in the battery bank. Renewable energy based AC electricity can be connected directly to this AC grid. In this mini grid, the DC power from PV modules is converted by solar string inverters (Sunny Boy from SMA) to AC power. It is worthwhile to mention here that both Sunny Boy and Sunny Island were developed in cooperation by ISET and SMA and are commercially produced by SMA. In this demonstration project the data logging is continuously being done in a dedicated logging system of 1 second resolution which is called ‘InTouch’ and additionally in the logging system of the Sunny Island inverter which is 1 minute resolution system. Procuring the original logged data from ISET, the primary data analysis was done using both types of data series for this Doctoral research. The figures 3.5, 3.6, 3.7 and the table 3.2 have been prepared out of these data analyses. These battery inverters have the capability to operate in droop mode [48, 54-56]. In droop mode the grid behaves in some respects similar to a normal grid powered by large conventional power plant. This behaviour is illustrated by exemplary data of one day in Figure 3.5. In the early morning, there is no power generation by PV so that active power is supplied by the battery inverters (negative value) and the frequency decreases below 50 Hz. At 8 am, PV generates active power which exceeds rapidly the load so that the surplus active power (positive value) charges the batteries and the frequency rises over nominal frequency 50 Hz. A very important innovation applied in Kythnos system is to obtain control capability based on grid frequency as communication signal for advanced battery management in addition to the already mentioned frequency droop concept. The battery inverters are tuned to vary the grid frequency for providing control information to the distributed PV string inverters and the load controllers. When the battery state of charge is low the grid frequency decreases and by sensing this change the load controllers trip and the consumption is reduced to match the low energy storage situation, protecting the batteries from deep discharging. On the other hand, when the battery bank is approaching full charge, the grid frequency increases and PV inverters are able to sense this in order to continuously de-rate the power outputs, protecting the batteries from overcharging. This behavior is depicted in Figure 3.5 at 1 pm when the frequency increases because the battery's state of charge has reached the upper threshold.

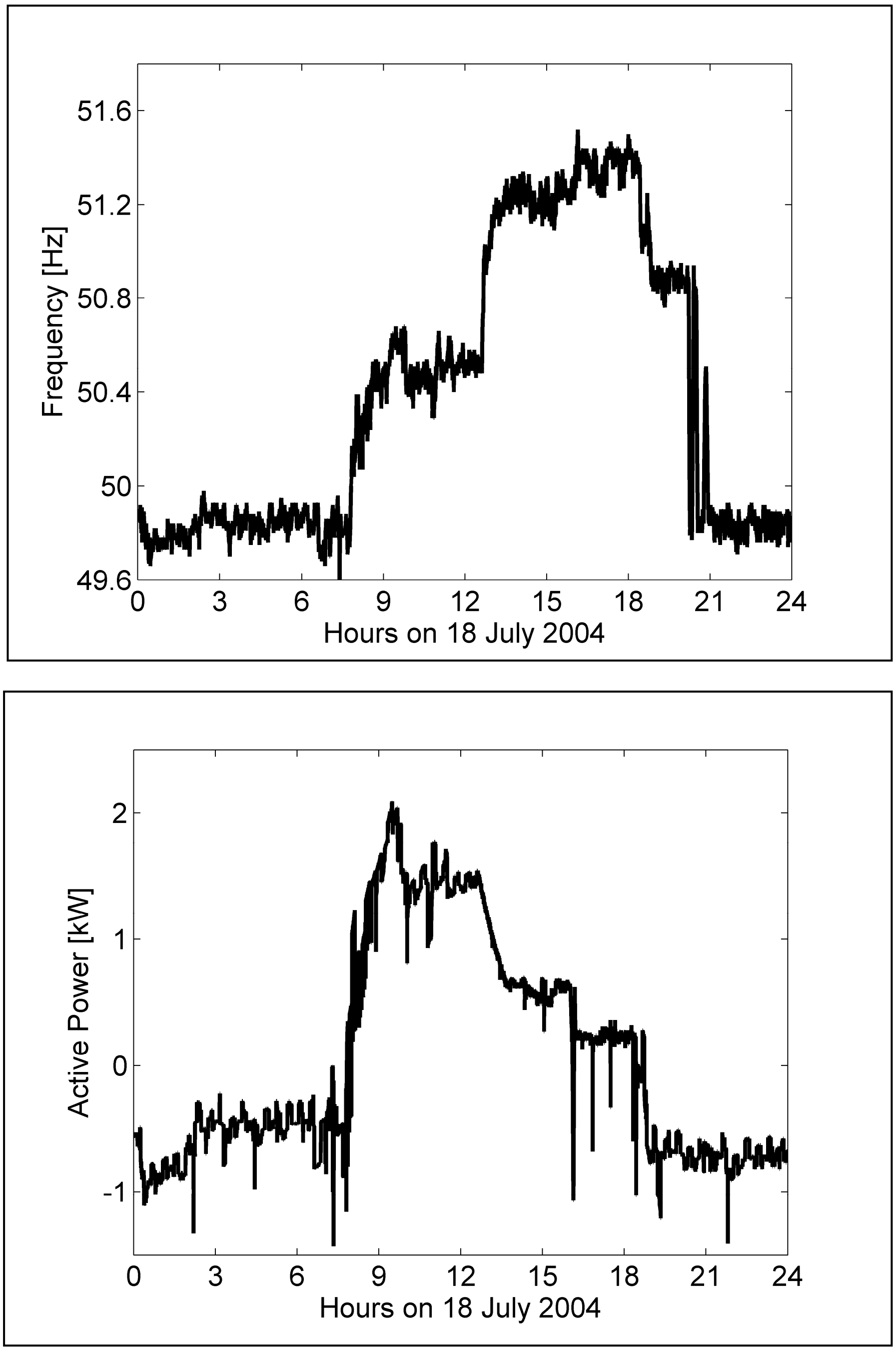


Figure 3.5: Frequency (left) and active power (right) at the terminal of the master battery inverter of the mini grid in Kythnos on 18 July 2004

Figure 3.6 provides more insights into the active power balance on this day. The positive envelope curve (during daylight, 7 am to 8 pm) of the stacked area graph shows the PV active power generation and the negative envelope curve shows the active power feed-in by the Sunny Islands from battery bank (at night, 7 pm to 8 am). During daylight, the PV generation provides active power for the loads, compensates grid losses and charges the battery. At 1 pm PV generation is reduced because the battery cannot be charged with the same rate anymore. When the PV generation is zero at night, the active power for the load and the grid losses is provided from the batteries. The diesel generator did not have to operate for the day. Vandenbergh et al. [53] show other details of the functioning of the Kythnos mini grid. Another aspect of the droop mode functionality of the Sunny Island is the voltage control according to the reactive power demand in the mini grid. This dependency allows sharing the reactive power demand equally between several battery inverters. Figure 3.7 provides these two values for the presented day. When the battery inverter provides inductive reactive power, the voltage is reduced from its nominal value (about 226 V) and vice versa.

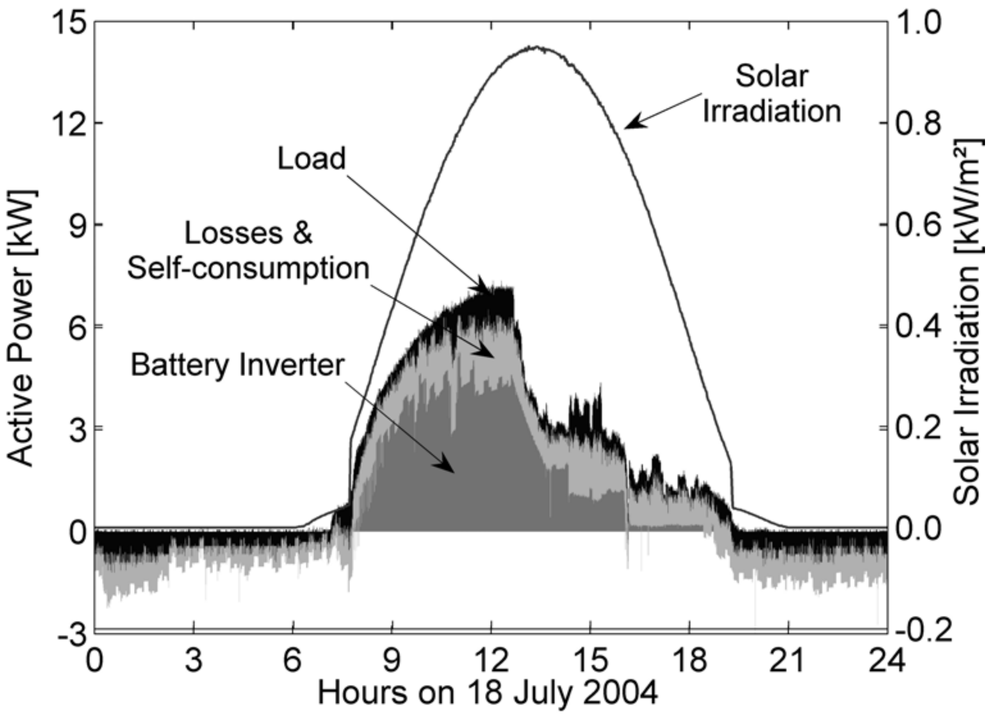
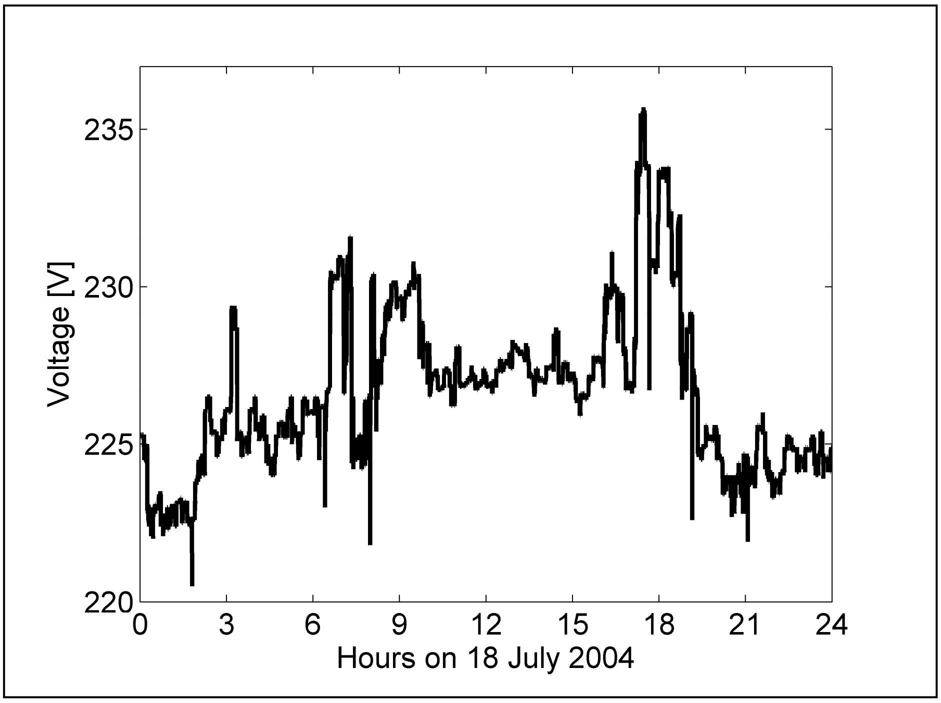


Figure 3.6: Active power balance of the mini grid in Kythnos and solar irradiation on 18 July 2004



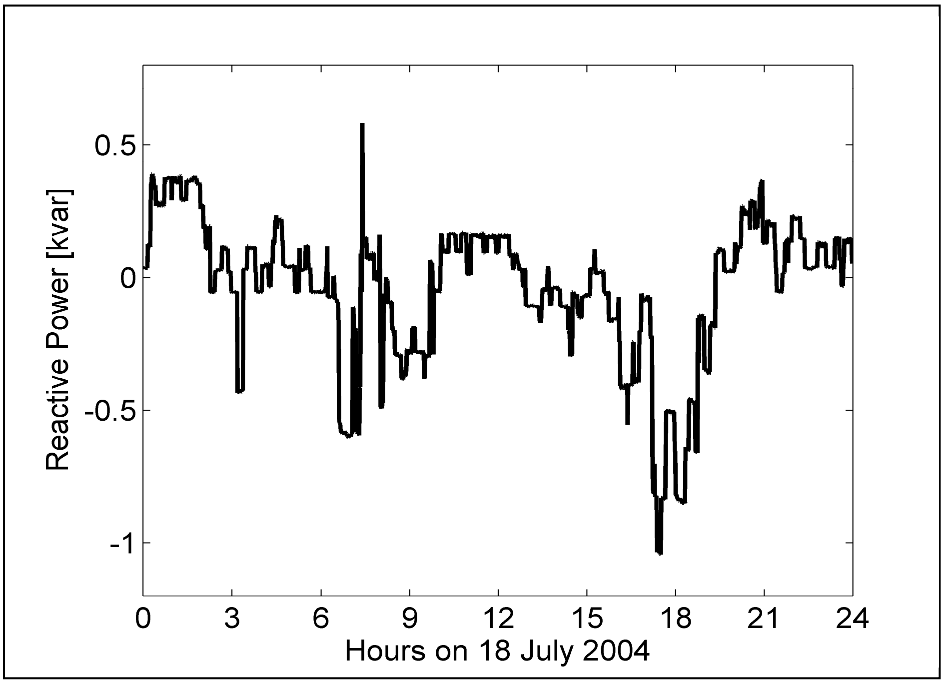


Figure 3.7: Voltage (left) and reactive power (right) at the terminal of the master battery inverter of the mini grid in Kythnos on 18 July 2004

The results of the data analysis are shown for a typical clear sunny day in summer on 18 July 2004. The global horizontal solar radiation on Kythnos PV field was 7.5 kWh/m^2. Table 3.2 gives the energy balance of this day. All loads were supplied from PV system only. About half of the load requirements were met from battery bank storage.

Table 3.2: Energy balance for 18th July 2004

Items	Energy (kWh)
Diesel generator	0
Sunny Boy PV output	39.2
Sunny Island input to battery bank	24
Sunny Island output from battery bank	14.5
Total external load including losses	29.7

3.7. Conclusion

An effort has been made in this chapter to review the existing definitions and outlooks on the nature of DG as a concept in general. This chapter discusses various features of DG deployment in Indian island cluster of Sundarbans. One of the key benefits of grid connected DG is the increase in service quality, reliability and security. A shift from traditional centralized control philosophy to a more distributed control style is provided by microgrids. This emerging concept is also reviewed in this article. They can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operations of microgrids require significant efforts in research, development and deployment of new technologies. In the light of DG and microgrids it can be stated that there exist several technical challenges to achieve ideal island power systems suitable for remote locations. Although large amount of research work still to be done, even today microgrids can be realized with commercially available components. These microgrids establish a reliable supply system and enable high quality electricity service for remote locations. A real DG project in Kythnos Island is concisely described in the article and primary plant data analysis is presented to show the successful operation of the system. It is probable that the usage of DG and microgrids in the remote islands of developing countries would increase in the future.

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Chapter 4

Methodology for small island electrification with renewable energy

This chapter begins with a quest to explore the methodology for designing renewable energy based electrification systems for the small islands in developing countries. The approach adopted here is a combination of published literature reviews and resources with own research work. As a result, a generic methodology is developed.

4.1 Introduction

This is well recognised opinion that the use of renewable energy applications can have multidimensional positive impacts on the island environment and help in sustainable development in general [1]. The need for different methodologies and models that will be helping tools for decision making procedures for exploiting local renewable energy sources is recognised in the world and different authors are proposing various solutions [1], [2], [3], [4], [5], [6] and [7]. A concise overview of various relevant publications can be found in [2] where the authors developed “RenewIslands” methodology in order to enable assessment of technical feasibility of various options for integrated energy and resource planning of island. However, the present study is restricted to the electrification system only. According to the draft IEC gudelines on rural electrification [8], the system of electrification consists of three subsystems viz. demand, production and distribution. There exist several constrains valid for all of these subsystems. The basic functional characteristics of electrification as a system are shown in the Figure 4.1.

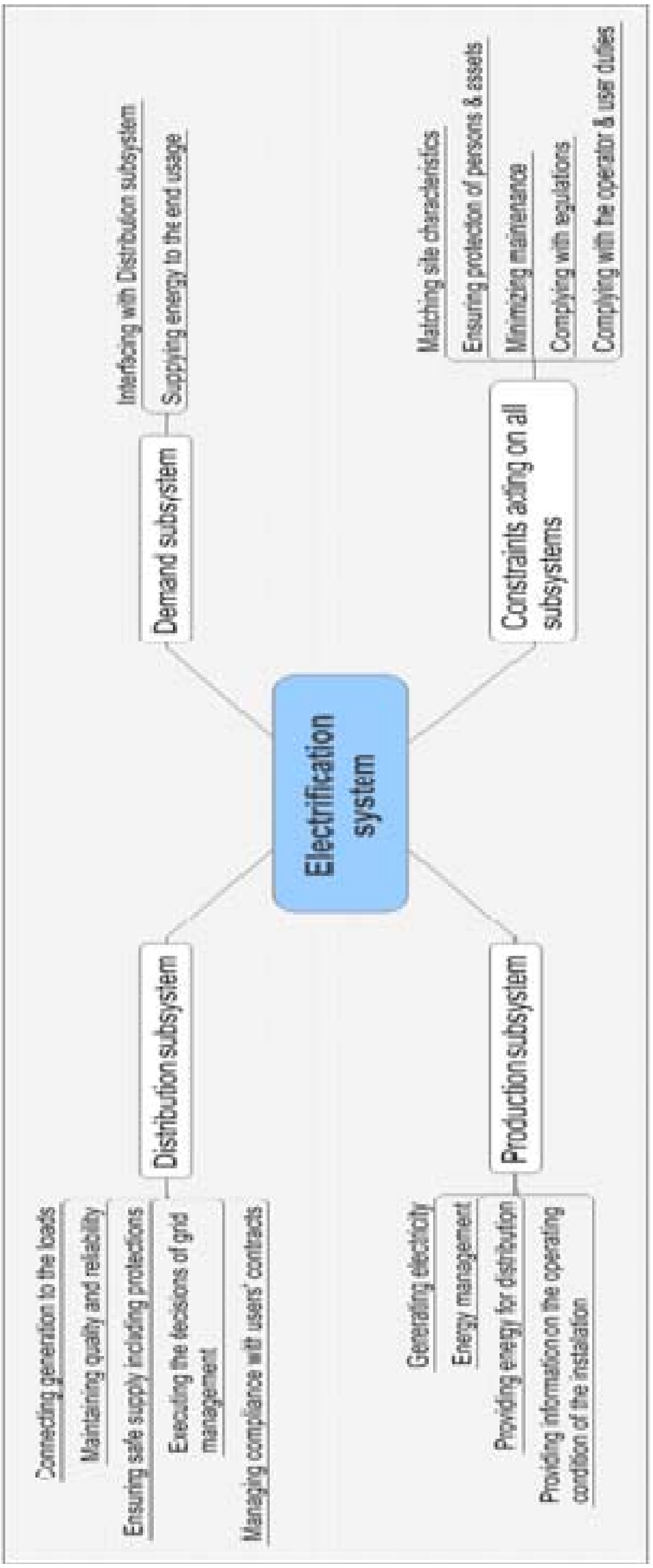


Figure 4.1: Basic functions of electrification system [8]

The World Bank [9] in their RE ToolKit website states that grid extension and off-grid alternatives should complement each other rather than compete. Experience in many developing countries shows that renewable energy mini-grid systems are an effective approach to expanding electricity service in certain rural areas. They have unique characteristics -- high investment requirements but low energy costs, fuelled by indigenous resources, and environmentally benign. Thus there is a need to determine the most effective options amongst grid extension, mini grid and stand alone small systems. Selecting optimum technology and arriving at the optimum system size are quite challenging task. According to the World Bank the key issues also include developing regulatory frameworks for mini grids, establishing effective institutional structures and supporting capacity building for business management, system design and operation. However, researching on these issues is beyond the scope of the present study.

4.2 Development of a generic methodology

The extension of grid-based power requires a minimum threshold level of electricity demand and certain load densities to be cost-effective. Deciding whether grid-extension or a mini-grid (or stand-alone) renewable energy systems are the least-cost option for supplying electricity to rural areas requires attention to the following factors:

- **Household service level:** the daily energy consumption of the average household

- **Total number of households to be served**: **Load density:** the number of households to be served per unit service area (in km^2) or by the number of households to be served per unit of distribution line (per km of low-voltage distribution line)

- **Productive loads:** the number and power requirements of productive loads such as rice mills, grain-grinding mills, water pumping, and commercial or service sector loads

- **Load growth:** the annual increase in the load that will result from increases in both the number of customers served and the demand for energy

- **Load curve:** the daily and seasonal variations in the power requirements

- **Renewable resource availability:** the nature and strength of the resource, which directly impacts the technology selection and system costs

- **Fuel costs:** these costs (including transport-related costs and fuel subsidies) determine the relative attractiveness of conventional mini-grids and hybrids systems

- **Electrification planning:** the long-term plan that utility planners may have for grid-extension to the region

The main system design factors suitable for island electrification system are identified and discussed in [8]. A comprehensive chart is developed by the help of [8] and presented in Figure 4.2. Lund et al. [10] has described the problems arise in relation to the intermittent nature of renewable energy sources and the fluctuations in their intensity throughout the day. The outcome of fluctuations in renewable energy sources and loads produces a situation in which substantial excess energy is sometimes generated, while at other instances there can be a lack of generated energy.

The higher penetration of renewable energy sources in islands, particularly more for autonomous systems, is limited with its intermittent nature, which can be increased to some extent by taking the following measures [11]

- some kind of energy accumulation (e.g. battery bank) is used

- additional controllable power generators (e.g. generators fuelled by biomass) are deployed

- demand side management measures are taken

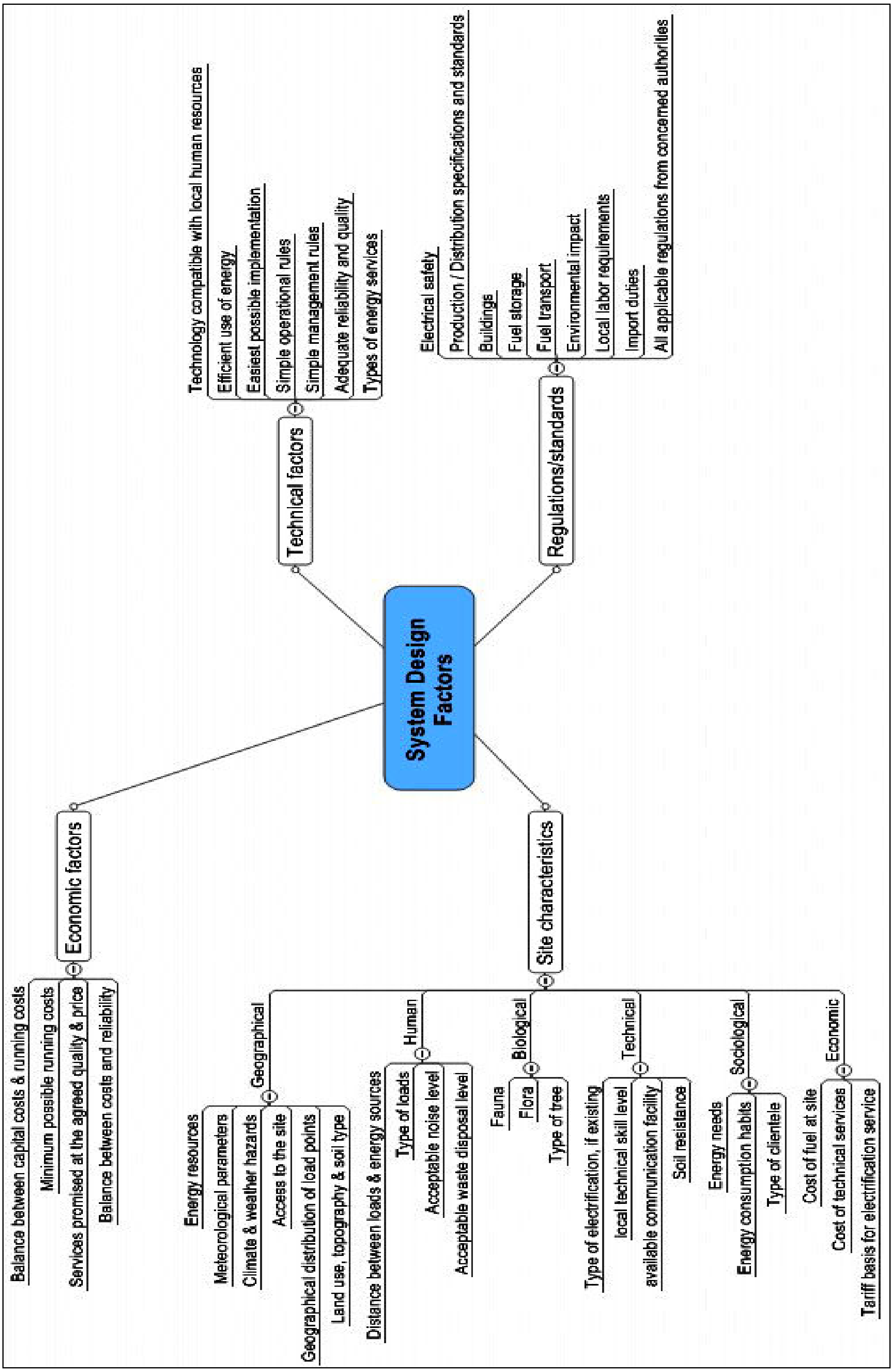


Figure 4.2: Basic island electrification system design factors

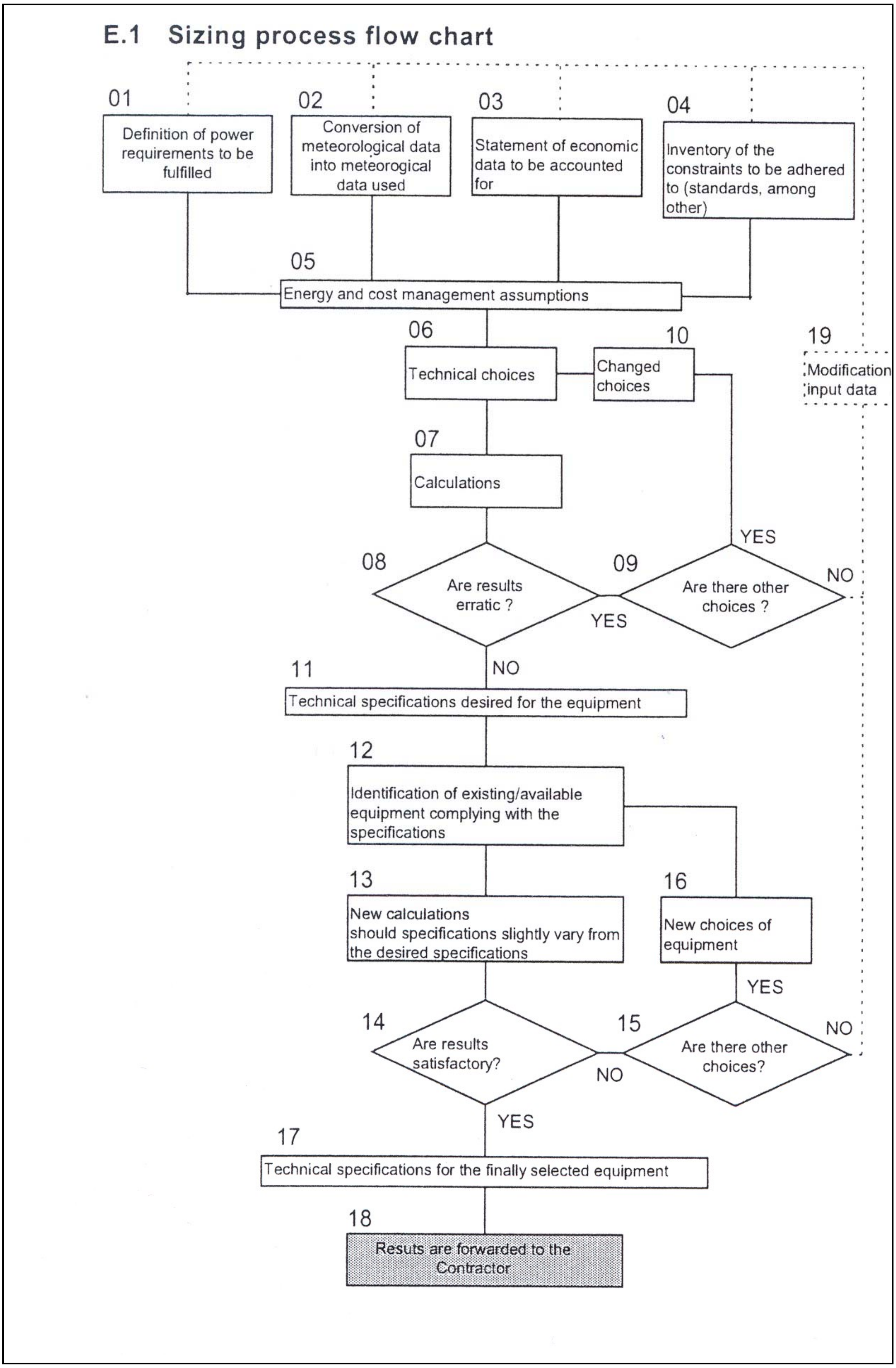
For a village energy supply by a local diesel power plant, the additional use of renewable energy based power like PV or wind, combined with an essentially smaller battery capacity enables greater supply reliability and system availability besides helping fuel economy [12]. For off-grid systems the use of renewable energy in conjunction with a diesel engine can increase the overall efficiency of the system and also allow the optimal use of the diesel engine by applying an optimal control strategy [13]. Because of high costs associated with battery storage, hybrid systems are suitable than PV-battery only systems, where backup generators enable an essential reduction of the battery capacity [14].

Duic et al. [15] has mentioned that because of the differences of the intermittence of a renewable source and the load, and when both are of the same order of magnitude, it is necessary to model the system on at least hourly basis, during a representative year. Various optimization techniques of hybrid PV/wind systems sizing have been reported in literatures including linear programming, probabilistic approach, iterative technique, dynamic programming, multi-objective techniques etc. [16]. IEC recommendation document [8] depicts a simple flow chart for sizing process which is shown in Figure 4.3.

The generic type methodology framework to arrive at the optimum island electrification design as developed in this research is shown in the figure 4.4. It should be clear here that applying this general framework in specific cases would necessitate addressing several new issues as would have arisen in case to case basis within each step of this proposed methodology.

The framework is simple and based on common sense and inspired by state of the art standards. The aim is to arrive at an optimum match point between technical potentials and managerial capability. The former depends heavily on the types of electricity demand, energy resources options, geo-spatial condition and state of the art concerning technology while the latter relates with organisation and business models, appropriate tariff structure, financing etc. In remote islands normally the focus is on the immediate and to a lesser extent medium term energy situations. Therefore it is important to account for the likelihood of changes in demand and/or cost situations in the short term planning horizon. Sensitivity analyses often become useful for this.

Fig 4.3: Sizing process flow chart as per IEC [8]



The key portion of this framework s to decide the most suitable option among traditional grid extension, 100% RE based power system and extending the grid along with local generation as support. Each of these three options has several aspects to consider and there can not be any general type solution for all cases. Each electrification initiative needs to be planned and tailor made to the specific situations. Techno-economic analyses addressing the estimated situations over the whole life time of the project are important.

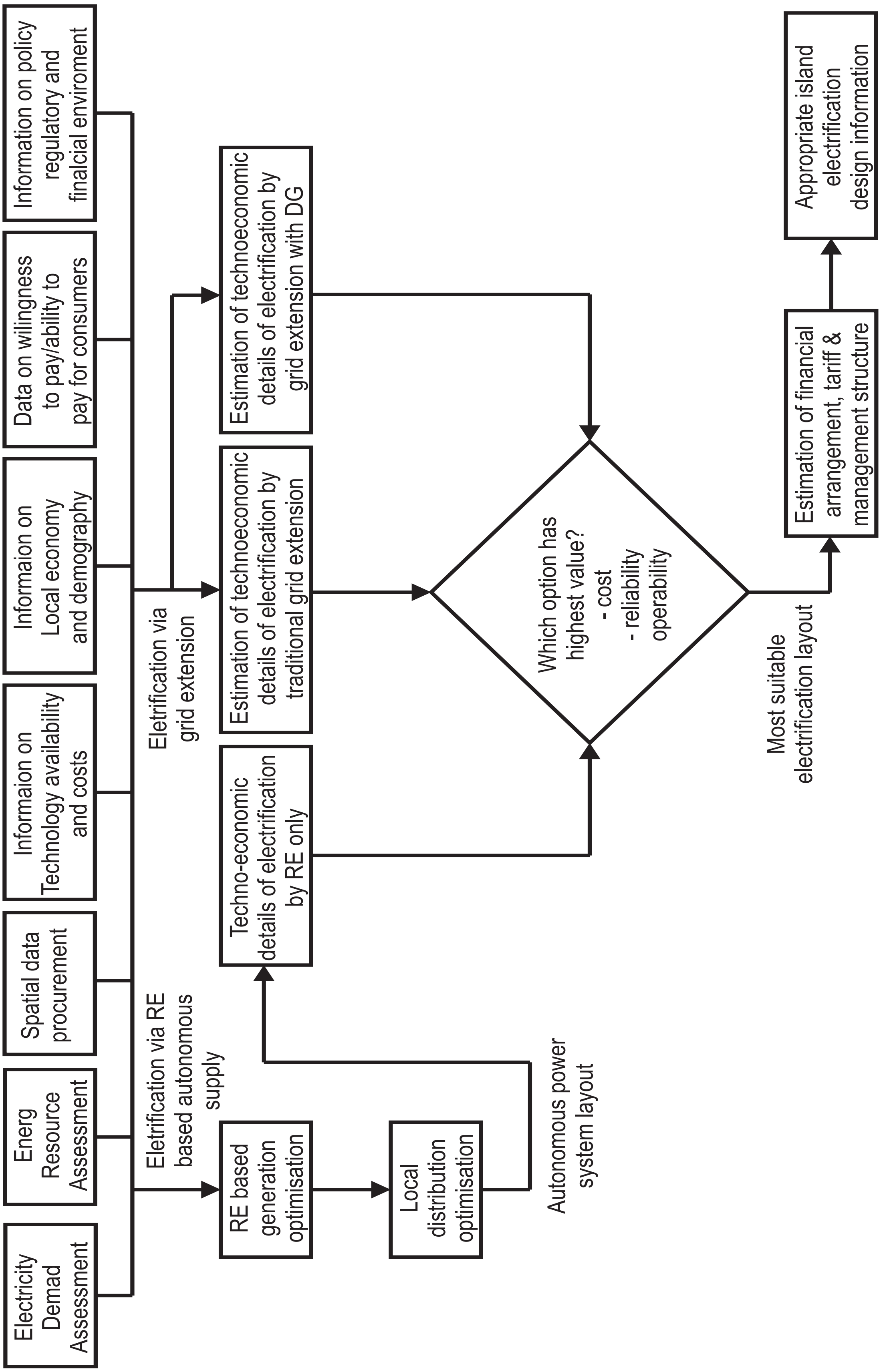


Fig 4.4: Generic electrification design framework

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Chapter 5

Case study in Sundarbans Islands

In order to apply the generic method developed in the previous chapter in a real world situation a detailed field work based case study has been undertaken in the island cluster of Sundarbans. This chapter records some of the important outcomes from the case study and addresses several technical issues while dealing with specific requirements of the case study. High attention has been provided in techno-economic aspects of electrification projects. The nexus amongst various factors influencing the final power system have been experienced by simulation.

5.1 Introduction

The generic type methodology for island electrification with renewable energy resources has been developed and reported in the previous chapter. Very obvious next step is to validate the developed method in a specific real world situation. However, it is not always possible to develop a real electrification project in a developing country island and also realize it within the framework of a dedicated doctoral study in Germany. In order to address this issue a detailed case study has been conducted within this doctoral research. This chapter describes about the case study. The Sundarbans Island region in India has been selected as the location of the case study. The specific reasons to select this island region for the case study include the following points:

1. India is a developing country with the largest population in the world without access to electricity. As mentioned in the Chapter 3, the drive towards electricity for all including remote rural areas through renewable energy has been recognised there.

2. Indian portion of Sundarbans island region represents a unique situation. The area is ecologically valuable. Over 50000 households already using

renewable energy as mentioned in chapter 3. But many more households still lack the access to electricity. Thus, it gives opportunity to experience the existing projects, the impacts of electrification on the island society as well as new chance to develop electrification projects in unelectrified areas.

3. The local electrification authority West Bengal Renewable Energy Development Agency (WBREDA) has been continuously trying to deploy various kinds of renewable energy technologies (viz. PV in several forms, biomass gassification, Wind-diesel-biomass hybrid etc.) in the islands. It gives, therefore, an opportunity to collect commercial information on costs of the plant components, management, tariff etc. as actually prevailing over the region.

Field visits were undertaken thrice. The objective was twofold:

- to get to know about Sundarbans region including the nature of the existing electrification initiatives therin
- to collect necessary information in order to develop academic case study for planning electrification on one unelectrified island

Extensive field works covering all existing plants in Sundarbans and many non-electrified areas were done during July – November 2005. In 2006 winter the field works carried out in Gosaba, Moushuni and Sagar administrative areas covering all PV mini-grid plants, Gosaba 500 kW biomass station and Sagar Wind-diesel-biomass hybrid system. In the winter of 2007 field work done for one non-electrified island called Bali, which has been selected for the present case study.

The information collected about the region, energy situation and particularly on the existing renewable energy projects are valuable for the knowledge gained under this research. However, in order to avoid a voluminous thesis document containing minute details, only very important data are presented here. Data are included here mainly related to the non-electrified island. More elaborate descriptions on the region and existing electrification initiatives can be found in other publications and reports made by the author [1], [2], [3].

5.2 Short general description on Sundarbans region

An introductory description on the islands of Sundarbans has already been given in chapter 3. ‘Sundarbans’ literally means ‘beautiful forest’. It is a vast tract of forest and saltwater swamp forming the lower part of the Ganges Delta, extending about 260 km along the Bay of Bengal from the Hooghly River Estuary (India) to the Meghna River Estuary in Bangladesh. The whole tract reaches inland for 100-130 km. A network of estuaries, tidal rivers, and creeks intersected by numerous channels, it encloses flat, marshy islands covered with dense forests. It is in fact world’s biggest inter-tidal delta region. It contains world's largest area of mangrove forests. The mangrove region of Sundarbans covers an area of 10,000 square kilometres, which is spread over India and Bangladesh. A number of rare or endangered species live here, including tigers, aquatic mammals, birds and reptiles. Government of India has declared 9630 square kilometres of area in Sundarbans as the Sundarban Biosphere Reserve. The total forest area is 4264 square kilometres out of which 1810 square kilometres are wetlands.

Indian Sundarbans is located between 21^{o} 32’ N – 22^{o}40’ N and 88^{o}00’ E - 89^{o}00’ E. This region has the boundary of Hooghly river in the west; Ichhamati, Kalindi, Raymangal rivers in the east; Dampire-Hodges line in the north and Bay of Bengal in the south. The region is criss-crossed with many rivers, rivulets, creeks and canals and has an agro-climate typical of a tropical coastal region. It has equable temperature with annual average temperature around 25^{o} C. Summer stays from mid March to mid June while winter is from December to January. Rainy season is from mid June till mid September. Annual average rainfall is about 1920 millimetres while average humidity is about 82%.

The wetlands of Sundarbans play a vital role in flood control with some of its mangrove plant species filtering water and removing sediments and pollutants. This region is particularly valuable as a repository of unique flora and fauna. This is also the homeland of Royal Bengal Tigers. The Sundarbans is home to many threatened and endangered species of flora and fauna. This makes the region a complex matrix of enormous biodiversity thriving on local rural system.

There are several interventions from various authorities to conserve and restore the ecosystem there. For example, Sundarban Biosphere Reserve area was established in 1989 and Sundarbans National Park was incorporated in UNESCO's World Heritage List in 1987.

About 4 million people live in Indian side of Sundarbans. There are two distinctive landscapes found within it. The first is more topographically stable main land where people have access to markets, schools, government offices, public facilities and utilities as they are not hindered by waterways. Roads and railways are within reach of this area and form dependable transportation and communication links for the population. Main grid systems also provide electricity in most of the areas there. The other category is larger and is composed of 102 deltaic islands out of which 54 are inhabited. The area comes under the State of West Bengal within two administrative Districts viz. South 24 Parganas and North 24 Parganas. There are 13 Blocks within South 24 Parganas and 6 Blocks within North 24 Parganas. It consists of 16 Police stations and 1064 villages. The State Government has formed a separate department – Sundarban Affairs Department to promote the development of this region.

In the islands, the main sources of livelihood are agriculture, (for example the cultivation of rice, chilli and betel leaves) and fishing. Honey collection from forest and forest waste wood collection also become means of living for the inhabitants. Firewood and dried cow dung remain the main fuels for cooking. Access to electricity is one of the key issues linked with energy security and overall development of islands of Sundarbans. The islands suffer from chronic shortage of electrical energy due to non-availability of grid quality power. It is extremely difficult to extend transmission lines from main land to these islands due to very wide rivers or creeks resulting in technical limitations and prohibitive cost. People depend on the expensive and often erratic supply of kerosene for their lighting needs. There are a few small diesel generator sets supplying electricity to the markets of some villages, but the diesel delivery mechanism is not reliable. As the region has the characteristics of sensitive ecosystem, remoteness, inadequate infrastructure for transport sector, distributed demand for electricity and dependency on petroleum products imported from main land, there is absence of diesel based grid systems. There exists little or no reliable access to communication systems, television, and health facilities, all of which requires electricity. Motorized and as well as manually operated boats are the common means of transport in the region. In many of the market places of the villages, there exist local entrepreneur based private electricity services for the shops through small sized diesel generator units. WBREDA's initiatives are bringing renewable energy based electricity access to over 50000 households at present. More electrification projects are coming up following government's policy to have electricity for all. There remain about 106150 households distributed in 131 villages in 20 islands still without access to electricity. The existing initiatives have already been summarised in Chapter 3. WBREDA's initiatives have been recognised with several national and international awards including the Green Oscar 2003 (The Ashden Awards for Sustainable Energy) and Eurosolar 2004 (European Solar Prizes).

5.3 The case study island: Bali

"Bali" is one of these 20 unelectrified islands and located between $22^{o}9'43.78''$N- $22^{o}3'23.66''$N and $88^{o}42'10.10''$E- $88^{o}47'50.04''$E with a total area of 37.79 km^2. The location of Bali within Sundarbans is shown in the figure 5.1.

Bali Island has five villages viz. Mathurakhand, Amlamethy, Bali, Bijoynagar and Birajnagar. **The present study was conducted for Mathurakhand and Amlamethy**. Figure 5.2 depicts the villages with Mathurakhand as highlighted portion.

As mentioned in chapter 4 on system design factors, the role of adequate spatial information is critical for any remote electrification project. The information on site topography, climate and hazards form compulsory requirement for the proper knowledge of site. In the Draft IEC recommendation [4], using topographical map with a resolution of at least 1:24000 of the surrounding area including 10 m elevation resolution has been suggested. Despite trying very hard to procure adequate spatial data on Bali Island nothing useful could be obtained. It was found out that **Bali Island is an area seriously limited by availability of documented data and effectively no spatial database**. In this point there remained two options to proceed:

1. Carry out own extensive ground survey to generate basic maps suitable for the purpose of this research

2. Try to create adequate spatial information by using Remote Sensing/GIS techniques

The first option was avoided because of long time requirement of organising the tasks along with high costs associated with it. It was felt it is worthwhile to approach via the second option even if it involves some degree of inaccuracy. The errors can always be reduced to acceptable accuracy at the end by "ground truthing" (field based validation). India despite being one of fast developing countries and the hub of information technology at present still lacks suitable spatial data in traditional form for remote locations. Thus there is a high probability that such lack of information can exist in remote islands of other developing countries as well.

Therefore a new research question has evolved from this situation: how to optimize time and cost of developing electrification plan at village level when there is no suitable spatial data readily available? Or in other words: **is it possible to approach towards optimum solution by using commonly available spatial data that can help reduce the burden of extensive field work at the onset of the design process at the local village scale?**

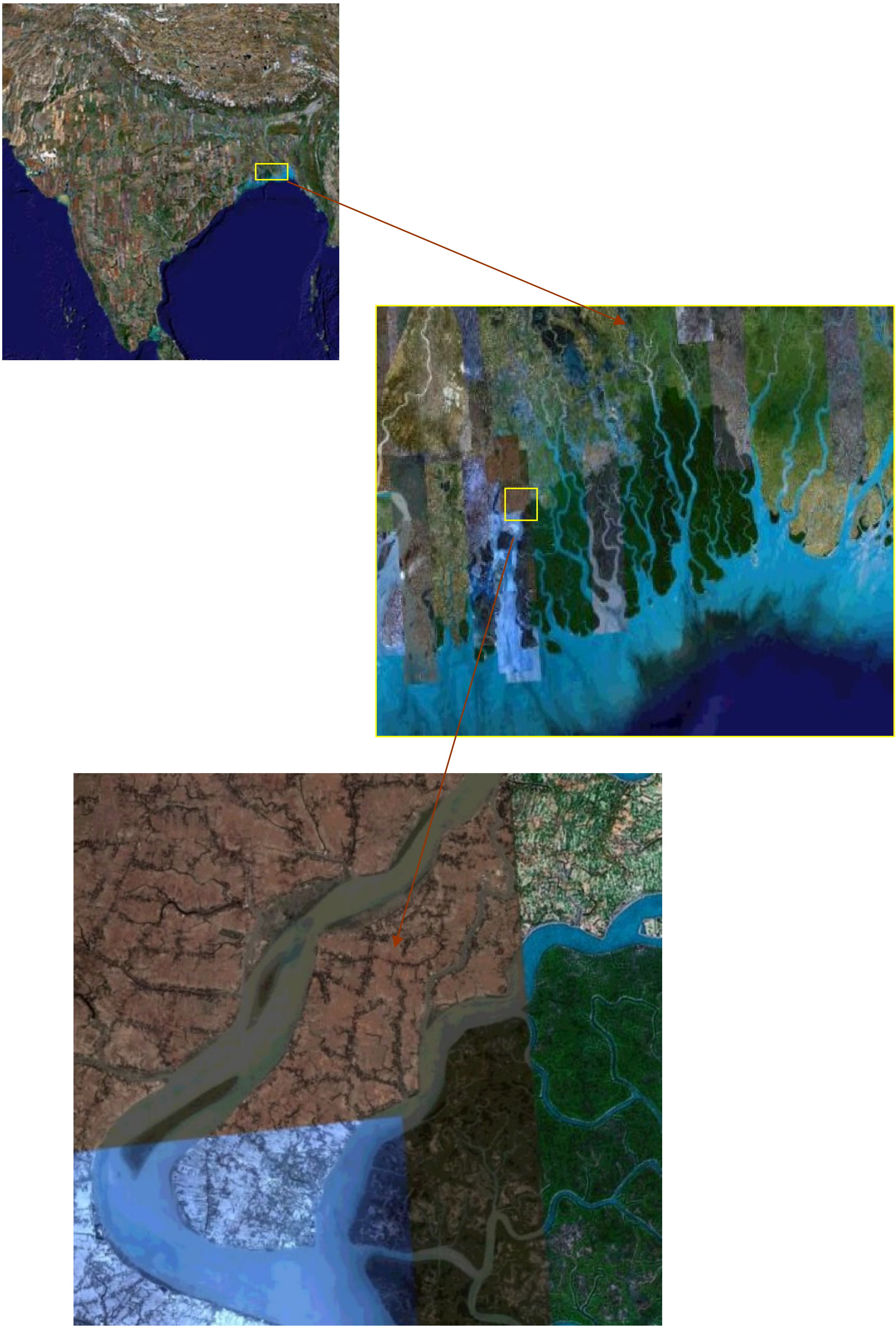


Fig 5.1: Bali Island in Indian Sundarbans

Fig 5.2: Administrative villages within Bali

5.4 Methodology adapted for this case study

The methodology adapted for this case study was kept in accordance with the proposed framework as presented in the previous chapter. Because of the remoteness and very low amount of electrical demand possibility the extension of traditional grid line by sea cable has been ruled out by the Government of India. As a policy, only renewable energy based power supply is being promoted therein. This case study therefore ignored the study on extension of grid option. The approach of this work included a combination of primary and secondary data collection, processing and interactions with identified stakeholders. Primary survey was carried out at the village level to assess the electrical energy demand. Secondary information collected and processed were related to spatial locations of the electrical loads, geographical features of the villages, land use, energy resources and technologies & equipments required for power generation and distribution. Attempt were made to utilize free of cost / low cost resources instead of purchasing expensive data sets. The current study enumerates an attempt for generating scenarios for electrification of a remote village in an island ecosystem under the added stress of non existence of spatial as well as documented secondary data through the use of high resolution remotely sensed image integrated into a GIS. The economic viability of the study is also high against the backdrop of having used freely available satellite imagery for the research. The key focus is to use the currently available tools in planning and management of electrification initiatives.

Application of remote sensing and GIS minimised extensive field based activities otherwise inevitable. Softwares used to accomplish the study were ERDAS IMAGINE 8.5, ArcGIS 9, HOMER and ViPOR. The first two softwares are well known and widely used in the remote sensing / GIS domain while the latter two tools were used on account of their high citation in relevant technical literature. They have been developed by NREL that possess extensive experience with RE technologies, the packages have many users worldwide and these two software packages currently can be downloaded free of charge from the internet. Efforts were made to simulate several system scenarios incorporating energy resources available. Techno-economic evaluation of each scenario was carried out to narrow down the focus at the optimum configuration for the power generating units.

Afterwards the optimum layout of the electric distribution lines was modelled to form a power supply system.

The methodology is depicted in the Figure 5.3.

In this phase of the research several authorities were contacted for collecting secondary information. Out of that names of some of the major are listed below. Its worthwhile to mention here that this specifically adapted framework does not have grid extension option at all. Only local power generation option, in form of mini-grids, is considered here.

List of few important authorities contacted:

1. West Bengal Renewable Energy Development Agency (WBREDA)
2. West Bengal Rural Energy Development Corporation Ltd.
3. Sundarbans Development Board
4. West Bengal State Electricity Board
5. Block Land and Land Reform Officer (BLLRO)
6. District Land and Land Reform Officer (DLLRO)
7. Panchyat and Rural Development Department (PRD)
8. Additional District Magistrate (ADM)
9. Block Development Officer (BDO)
10. Savapati (chief of administrative Block level administration)
11. Pradhan (chief of grass root level administration)
12. Bureau of Applied Economics & Statistics

The following data were collected from the above mentioned authorities

- Renewable energy resources over the region of Sundarbans
- Use and distribution of land in each block
- Statistical data on demography of the region

- Biomass plantation related issues including land availability for energy plantation

- Details about the existing power plants in the region

- Load pattern, load growth and consumer behaviour in the existing plants

Besides, product details of different renewable energy technologies were collected from WBREDA.

The entire case study has been developed in three subsequent phases**. In the 1st phase an approximate solution is developed with the help of commonly available Remote Sensing / GIS technique. In the 2nd phase the accuracy obtained in 1st phase has been increased by ground validation of the spatial data. In the 3rd phase artificial scenarios were generated for experiencing the sensitivity of a few key factors on the final power system structure.**

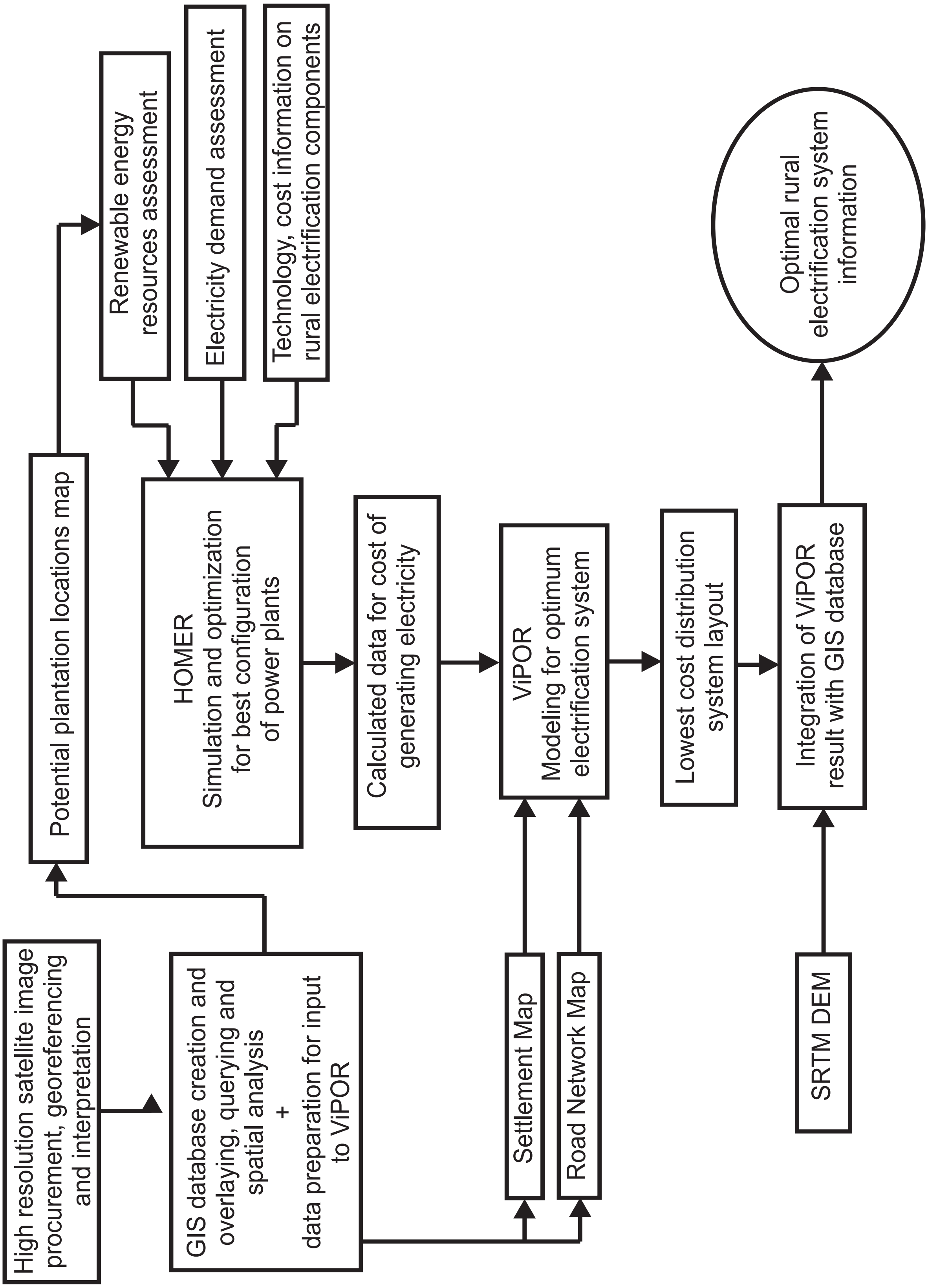


Fig 5.3: Adapted methodology for the case study

5.5 Applications of Remote Sensing and GIS for this case study

After a thorough exploration of all possible sources of database availability, cost of procurement and ease of processing and handling, Google Earth was found to be a suitable gateway to the procurement of free high resolution imagery. Use of high resolution imagery in this case was found to be of substantial importance in order to map settlements for electrification. Quick Bird imagery (December 2002) was downloaded from the Google Earth server. PAN resolution of the imagery is 0.6m and MSS spatial resolution of 2.49m with 8 bit data. The unavailability of referenced paper maps or previously referenced imagery of the area necessitated the use of Google Earth for input of GCPs (Ground Control Points) for georeferencing. The georeferencing was carried out in ERDAS Imagine 8.5 and final mosaic of the area was prepared for further database preparation. The final mosaic was projected to Geographic Lat Long with WGS 1984 as datum. The five villages within Bali Island were subset from the entire imagery after delineating the administrative boundary available from National Atlas & Thematic Mapping Organisation, scale 1: 50000. The subset imagery was used for further processes.

Spatial data was generated for the two villages Mathurakhand and Amlamethy and the layers for road network, settlement and the potential areas for biomass plantation were digitized from high resolution imagery in ArcGIS 9. The majority of the land is being used for agriculture as seen in the imagery. Settlement pattern shows clusters developed in proximity to roads. A total of 228 settlements were mapped from the satellite imagery for the village Mathurakhand and similarly 387 settlements were mapped for Amlamethy. Spatial querying and analysis tools in Arc Map were used and data was exported for further application in ViPOR.

The Shuttle Radar Topography Mission (SRTM) is a joint project between the National Geospatial Intelligence Agency (NGA) and National Aeronautics and Space Administration (NASA) launched on February 11, 2000. The mission aims to provide digital topographic data for 80% of the surface of the earth. Digital Elevation Model (DEM) at 3 arc second (90 m interval) is freely available at the SRTM website India. DEM for Bali was extracted and values were subset from the larger dataset available. The DEM can be useful to calculate lengths of the electrical network along the topography. However, in the present case study using a DEM does not have substantial significance since there is no considerable variation in elevation, the maximum height being 11m above mean sea level.

5.6 Renewable Energy Resources

5.6.1 Solar Resource

Sundarbans is blessed with good solar resource. Average annual solar radiation is about 1800 kWh/m^2 on horizontal surface. In a year there typically are 250 sunny days and 55 totally overcast days. The annual average solar radiation on horizontal surface is about 4.91 kWh/m^2 per day. The ranges of daily global solar radiation in different months are shown in Fig 5.4 while those in different hours of the day are depicted in Fig 5.5. NASA's surface meteorology and solar energy database (release 5.1) was utilized for the solar radiation data [5].

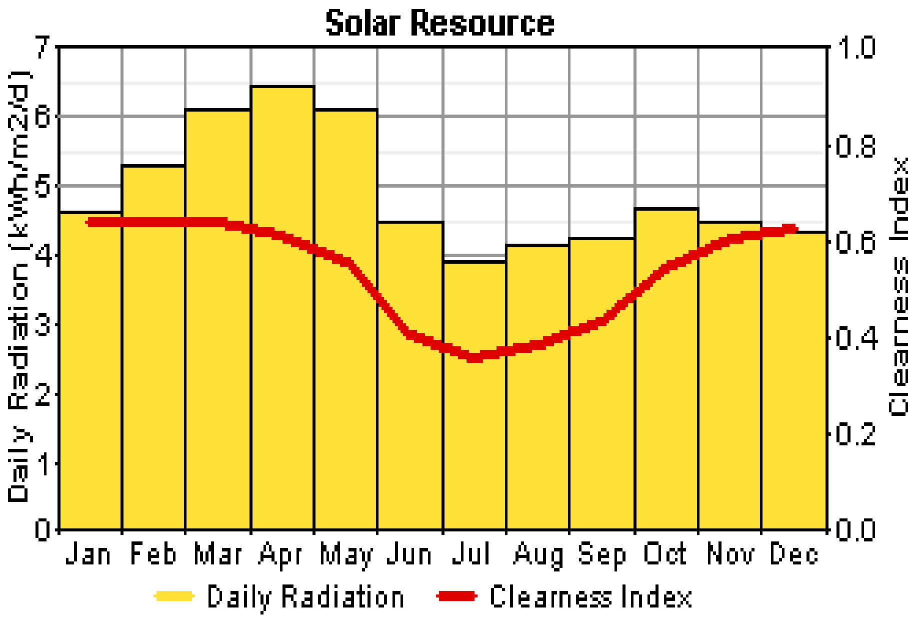


Fig 5.4: Monthly averaged daily solar radiation on horizontal surface in Bali [5]

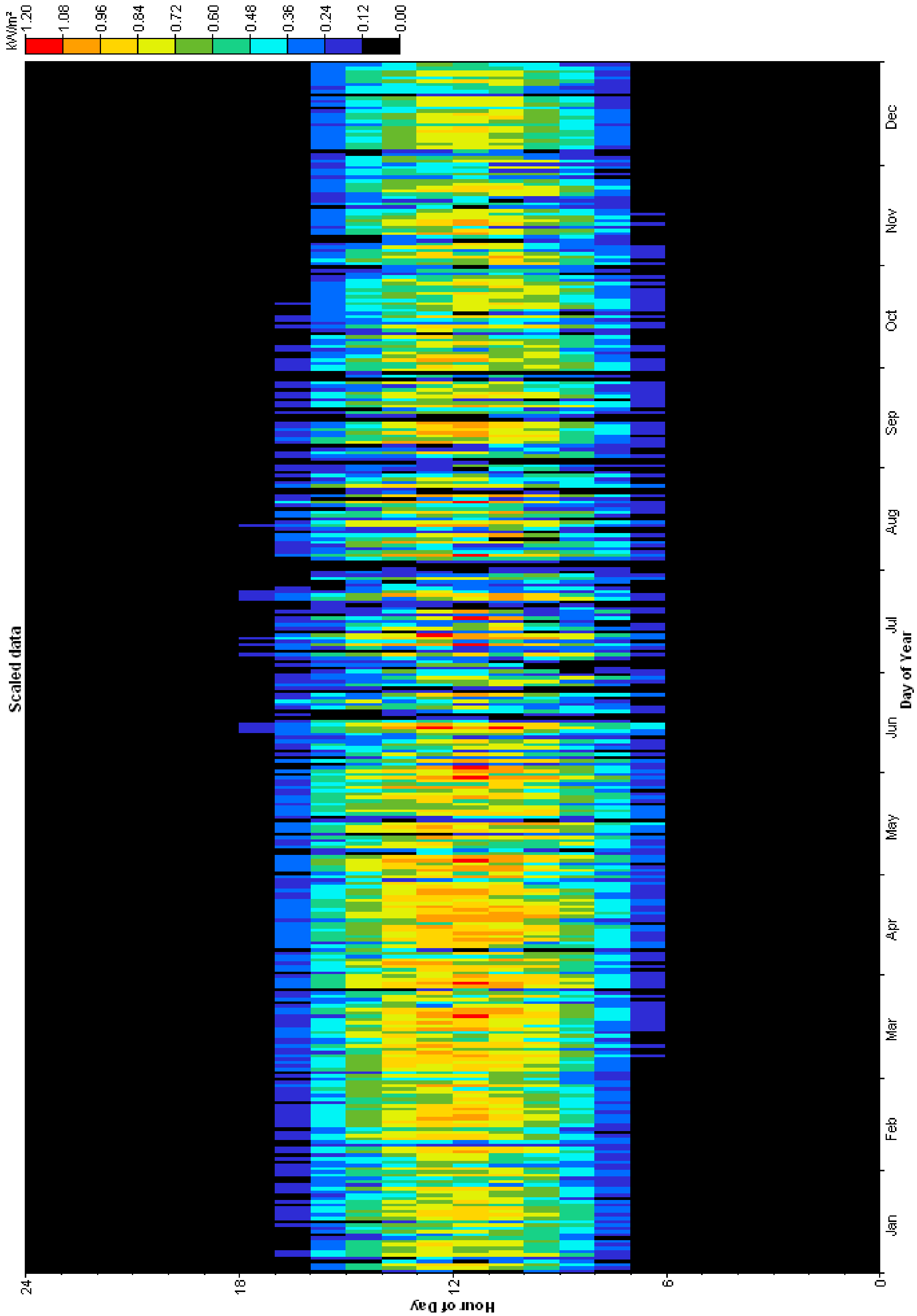


Fig 5.5: Global solar radiation over Bali Island

5.6.2 Biomass Resource

In general, Sundarbans region, a forest area, has rich biomass resources. Availability of woody biomass for power generation and land availability for energy plantation were the two options that were explored through secondary data analysis as well as through GIS operations. In and around Bali Island there are elongated stretches of open land embankments which are called ‘char lands’ in local administrative terminology. As part of the study preliminary results of the areas are presented here that may be available for energy plantations. Attempts to plant mangrove species, ‘Acacia arabica’ and ‘Subabul’ have been made by WBREDA in adjoining islands which encourages similar practices in other areas [6]. From the GIS results, in Bali Island itself there exists around 1.8 square km of char land. The energy plantation in nearby islands gives sustainable yield of around 3 metric tones per hectare per annum [3]. According to the “District Statistical Handbook 2003”, published by the Bureau of Applied Economics and Statistics, Government of West Bengal, there exist 6778 hectares of vested land within the administrative Block Gosaba, which are still not distributed. In nearby islands plantations have been done in over total 80 hectares by WBREDA and the local administrative government (Panchayat) forming separate committees for management. It is expected that most of the requirements could be met by plantation in Char lands / vested lands / canal side / road side space etc. spread over the entire South 24 Parganas District. Another source of biomass supply is by way of purchasing from social forestry wood stock. WBREDA is already utilizing all of these means for its existing biomass plants in a neighbouring island called Gosaba. It should be noted here that no detailed biomass potential assessment was conducted for this study. It is necessary for a commercial project to conduct field studies with respect to the actual potential of the char lands, based upon the quality of the land and soil, actual current use of the char lands, productivity estimates of select woody biomass species in the existing soil conditions etc. IPCC reports that potential sustainable development synergies and conditions for implementation are mostly positive when practised with tree trimmings. However, can have negative environmental consequences if practised unsustainably [7]. The energy plantation issue involves managerial and financial aspects for sustainability which were excluded from the scope of this study. It was assumed in the current study that the biomass supply will be made available from any or all of the potential supply chains.

5.6.3 Other Energy Resources

In entire Sundarbans region there are two locations, namely Ganga Sagar and Fraserganj, where CWET (Centre for Wind Energy Technology, Government of India) has established wind-monitoring stations and published wind data. Both Ganga Sagar and Fraserganj monitoring stations were at the seashore. For this reason locations near these two places with closeness to seashore would have less variation in wind profile compared to that of the measured one. For entire Sundarbans islands orography remains similar, as the region is flat with mean altitude near mean sea level. However, the surface roughness varies from location to location and obstacles in the form of high trees and buildings might be present. Bali, being located far from those two monitoring stations, has no monitored wind data and therefore was excluded from wind resource utilization in this study.

Other kinds of resources include potential application of tidal energy and biogas power. WBREDA is working on a proposal of building up a tidal power plant of 3.6 MW capacity near Gosaba Island. Sundarbans does not have any experience with biogas based electric plants so far. It should be mentioned here that WBREDA has much wider spectrum of successful projects outside Sundarbans in its portfolio other than PV, biomass gassification and wind which includes biogass plants, microturbines, small wind turbines, waste to energy projects, small/min/micro/pico hydro plants, solar desalination, PV water pumping etc. and many other applications of heating service like improved cook stove, solar cooker, biomass gasification based heat from agricultural residues etc.

The coverage of the present study was confined to solar PV and woody biomass gasification based electricity generation. These two are technically proven renewable energy technologies having adequate working experience in local areas. Diesel based power generation was considered for creating the baseline scenario.

5.7 Electricity Demand

It is extremely difficult to scientifically estimate electricity demand of a non-electrified and remote village which is located within a greater non-electrified region. From the information on ability to pay and willingness to pay by the villagers (from door to door survey or otherwise from secondary data) and prevailing expenditure on energy services and government policy on electrification etc., approximation can be made. However, this still would be a roughly estimated value. **It is impossible to accurately calculate for the first time the need for electricity service which has never been tried so far in a village**. If nearby areas are electrified then it becomes easier for the villagers to estimate on their probable demand of electricity and experience becomes important.

Bali Island is completely non-electrified. However, the neighbouring island Gosaba is partially electrified by biomass gassifier power station.of 100 kW x 5 capacity. Also several mini grids exist in many other islands of Sundarbans. This awareness helped to estimate the electricity demand in Mathurakhand and Amlamethy villages within Bali Island. There is no significant variation in the life style, income level or general attitude towards using renewable electricity among all islands in Indian Sundarbans. People are happy to have electricity in their homes. People from non-electrified areas are keen on getting this service. Very large numbers of fresh applications for new connections are lying with WBREDA office. **This fact is perhaps enough to estimate the demand with the help of WBREDA's experience in other islands.** In addition, in order to estimate the demand more scientifically, **ground survey was conducted** in the households' level as well as in the market places.

It was found that in almost all locations, people use kerosene for lighting purposes and the kerosene consumption varies from 4 litres to 7 litres/month per household with a price for kerosene as Rs. 30/litre. The access to electricity is one of their priorities and most of the households are interested to take the service connections. It was estimated that demand per household would be approaching 30 kWh per month with duration of supply for at least 8 hours per day. It was found that people need electricity for two hours (4am-6 am) in early morning for different domestic purposes and 6 hours (6pm-12pm) in the evening. This service of 8 hours also follows the current standard practice of WBREDA in most part of Sundarbans region [1]. **From the satellite image and the corresponding GIS layer prepared, without ground validation, it is not possible to perfectly distinguish the nature of settlements i.e. households or shops or schools. Therefore 1st phase of analysis was performed assuming all settlement points as households**. In 2nd phase of analysis a dedicated section on ground validation is included where all types of loads were separately considered in analysis. The community loads like schools, student dormitories, video halls, health clinics etc. were also included in the survey. There is no demand for water pumping for drinking / irrigation purpose in these two villages. There are small capacity diesel generator sets in the markets run by private operators.

From the experience of existing plants in the Sundarbans region run by WBREDA a very low diversity factor is expected. Therefore diversity factor of 1 was considered in the demand calculation for households. In this 1st stage only a simplified demand profile was considered in the sense that variations over the season and daily and hourly fluctuations were not taken into account. In the 2nd phase of analysis more realistic estimation of total demand has been attempted. For the total 228 households in Mathurakhand the estimated annual average electricity demand is 228 kWh per day. This load profile has estimated maximum peak load of around 28.5 kW with a load factor of 33.3%. Similarly for Amlamethy village the estimated annual average electricity demand is 387 kWh per day with a peak load of 48.4 kW.

Interestingly, Santos and Kleinkauf [8] have shown that the consumption of structure of small and moderate sized communities can be characterised by the mean value of their energy consumption and through their daily load curve. They have proposed a methodology that enables the modelling of power demand data sequences based on stochastic processes. The resulting model requires the monthly averages of energy consumption and the load factor as input data. So, based on different hypotheses of both energy consumption and load factor different sequences of hourly power demand data can be generated. According to their data availability, their model works well if mean load factor falling between 0.35 and 0.75, provided the peak load occurs between 6 pm and 12 pm. In this case study this synthetic demand estimation procedure was not used.

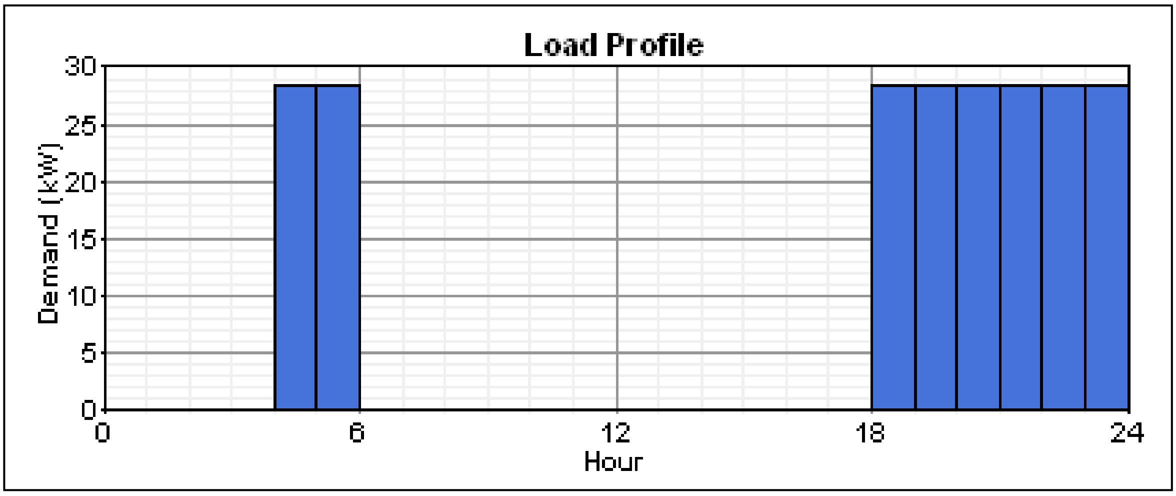


Fig 5.6: Simplified demand profile for Mathurakhanda

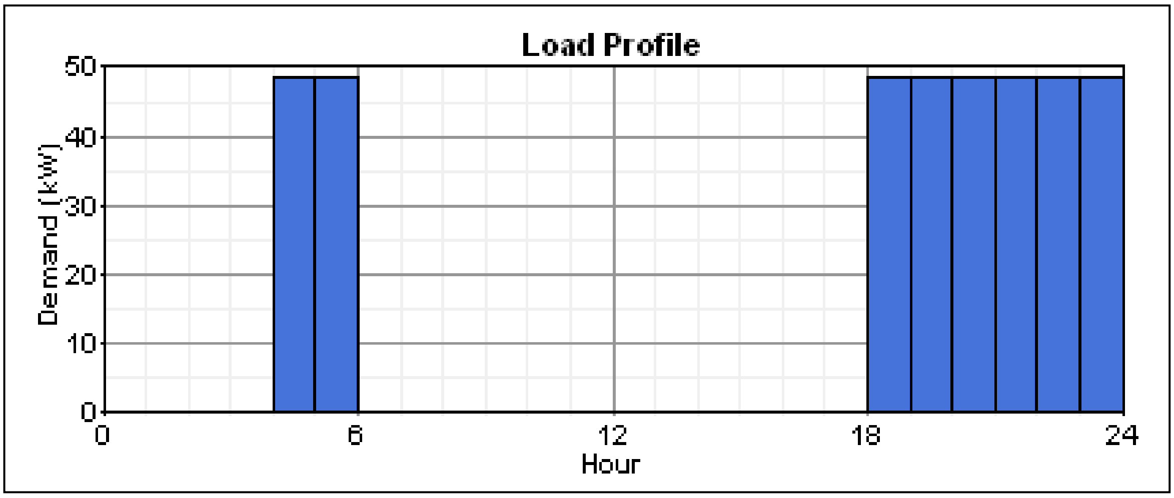


Fig 5.7: Simplified demand profile for Amlamethy

In principle, application of demand side management (DSM) is important for energy management of renewable electricity service resulting in better utilization of expensive resources. There are many publications proving importance and usefulness on this. However, DSM is commonly promoted, regulated and encouraged by the government or electric utilities. Policies that increase energy efficiency both on the demand and supply side, are pursued to reduce demand for energy without affecting, or while increasing, output at low costs. This is the case even though some of the direct efficiency gains might be offset by increased demand due to lower energy costs per unit of output. Efficiency also increases competitiveness and lowers expenditure on energy thereby freeing up more resources for other development goals [7]. The ultimate freedom to consume electricity at any efficiency level may lie with the end user, just like in a big city. DSM is not addressed in this research.

5.8 Simulation studies for electricity generation

Instead of establishing power supply systems based on single RE sources, exploiting energy from different sources enhances the reliability and capacity factor and improves the plant economics. Therefore, technological options explored were based on hybridisation of RE technologies depending upon resources available locally. With this philosophy, efforts were made to simulate and analyze a large number of alternative system configurations. Thereafter optimization analyses were carried out to arrive at the best possible sizing configurations. For this task a tool called HOMER (version 2.42 beta) is used. The characteristics and capabilities of HOMER have been explained in details in the Chapter 2. There exist many references of using HOMER as a simulation tool including Nfah, E.M. et al., 2008 [9]; Rehman, S. et al.,2007 [10]; Georgilakis, P.S., 2005 [11]; Khan et al.,2005 [12]; Shaahid, S.M. et al.,2004 [13]; Lilienthal, P. et al.,2004 [14] etc.

Solar Home Lighting sytems were excluded from the coverage of analysis as the quality of service provided by them is fundamentally different than a normal mini-grid system which approaches similar features of a traditional grid connected system.

Product details of PV, biomass gasification and diesel generator based energy technologies, along with cost estimates, **as actually prevailed in other islands** in Sundarbans, were collected for calculations. The values of the parameters generally follow the actual situation in the year 2006-2007 and so **can academically be claimed as realistic**. However, it may be appreciated that **these costs are indicative** only, and for a new project these may vary from location to location and project to project depending on the dynamic business environment of India. Normal lead acid solar battery, 30 kWp PV system units and 100% producer gas based biomass gasification electricity units were considered. PV array tilt angle was assumed to be fixed at the angle of latitude. These are standard practice in the other plants in Sundarbans. In order to perform the analyses, development of a HOMER model for biomass gasifier generator unit has been specially carried out.

Various important capital cost parameters assumed in the calculations are given in Table 5.1.

Table 5.1: Data on costs for power generation units

Item	Capacity	Cost (USD)
PV module & accessories	30 kWp	151718
Inverter & accessories	30 kW	54583
Battery bank & accessories	800 Ah, 2VDC, 120 nos.	25200
Gasifier generator system	40 kWe	50000
Gasifier generator system	20 kWe	25000
Gasifier generator system	10 kWe	20000
Woody biomass	1 kg	0.025
Diesel generator	30 kW	7125
Diesel generator	13.5 kW	6050
Diesel fuel	1 litre	0.875

The following assumptions were made on economic parameters

- 7.5% as ‘Real Interest Rate’ has been used as the effective rate of interest to nullify the influence of inflation in the calculation
- 1 US Dollar (USD) = 40 Indian Rupees (Rs.)
- 1 Euro = 60 Indian Rupees (Rs.)
- Project lifetime = 20 years

Scenarios based on diesel only, PV only, biomass gasification only and PV-biomass hybrid power stations were developed for the analysis. As HOMER calculates in US Dollar, all costs have been converted from Indian Rs. into USD and afterwards the calculations have been performed. The tables and graphs show the costs in USD, as given by HOMER’s output windows. In selected cases the output costs have been re-converted from USD into Euros to develop customised graphs outside HOMER.

5.9 Modelling for distribution systems

A survey was conducted in order to find the suitable tool to be used for this portion of the caser study. Several electric utilities in Germany and India have been contacted to know their standard practices. In addition to this, power modeling software developers, firms of consulting engineers and institutes at universities are covered in the survey. NEPLAN (CALPOS), Elektra, PSS^{TM}SINCAL, PowerFactory and Integral: these software were also explored. **The result of the survey came out to be that at present there is no software tool readily available which can perform a complete optimization task necessary for a green field planning**. Also, utilities use their rules of thumb design practises with the help of their experience. As an example in rural areas in Germany, every 200 to 400 m (in average 300 m) a step-down transformer from medium to low voltage (typical rated power: 630 kVA) is placed. Coming from these local transformer stations low voltage cables (typically 4 x 150 NAYY) are installed along all adjacent streets. Whereas in the electrified mainland areas within Sundarbans region, single phase overhead feeders of 15 kVA are quite common.

From the literature review **only one software tool named ViPOR has been found which can be used** for autonomous renewable energy power supply systems that fulfil most of the requirements of this case study. Therefore ViPOR (version 0.9.23) is used here. This is a 32-bit Windows application written using Microsoft Visual C++ and developed by National Renewable Energy Laboratory, USA [15]. ViPOR is developed for optimization of village electrification process. The capability of this tool has been published in details in the article by Lambert, T. et al., 2000 [16]. The introduction about ViPOR has been already given in Chapter 2. The limitations of it are also listed there. While working with ViPOR in this study, a few additional weaknesses, like error in the HOMER-ViPOR integration, and the output features etc., were detected. These were brought into the attention of NREL and afterwards by their cooperation the accuracy and features were improved.

Indian system of 50 Hz, single phase, 240 Volt AC is typical for electrified remote villages. Single phase 3 wire over head AAC conductors of 30 mm^2 with PCC pole structure were considered for 0.240 KV low voltage distribution, which is typical for the rural electrification schemes in the Sundarbans region. For medium voltage power evacuation, 11KV over head, 3 phase 3 wire, 30 mm^2 ACSR line were considered. Service connection charge for the households was considered along with energy meter in the analysis. **The locations of the households were exported from the GIS settlement layer. The road and land use layers were also used in the input parameters for the calculation in ViPOR**. It was assumed that the cost of distribution line along the road side is cheapest while across agricultural field is 1.5 times costlier and across water it is 10 times costlier. Two sets of calculations were made, one without considering these cost variations and another incorporating these. The values of the parameters related to the equipments of distribution network were collected from WBREDA, who has several electrification projects in different islands throughout Sundarbans region and shown in the table 5.2.

Table 5.2: cost data for distribution

Item	**Capacity**	**Cost (USD)**
LT, 0.240 KV, over head, 1ph. 3 wire, 30 sq. mm, AAC	1 meter	4.25
11KV over head, 3ph. 3 wire, 30 sq. mm ACSR	1 meter	8.5
Step up transformer 3ph, 0.433/11 KV	60 KVA	2875
Step down transformer 1ph, 11/0.240KV	5 KVA	200
Service connection per house	Including energy meter	100

5.10 Results of Phase 1

The scenarios were built up for the following situations

- Generation study for Mathurakhand and Amlamethy individually
- Generation study for a central station serving both villages
- Distribution study for individual villages

- Distribution study for the central scheme

In all of the calculations a relaxation up to a maximum total annual capacity shortage of 5% was allowed.

5.10.1 Results for the village Mathurakhand

Baseline calculation by diesel power plant:

A diesel generating plant of 30 KW capacity was considered for the baseline case as diesel generators are very common in remote rural electrification schemes. For the 228 kWh per day annual average electricity demand for the village Mathurakhanda, the simulated system performance indicated that 83220 kWh of electricity will be produced with a total net present cost (NPC) of 302400 USD (Euros 201600) and a levelised cost of energy (COE) production of 0.356 USD per kWh (0.24 Euros/kWh). The initial capital cost will be around 7125 USD (Euros 4750). Total diesel oil usage would be in the tune of 27815 litres per year contributing to annual emissions like 73240 kg carbon dioxide, 180 kg carbon monoxide, 150 kg sulphur dioxide, 1600 kg nitrogen oxides etc. It should be noted here that diesel fuel based power stations in the region of Sundarbans are not encouraged by the Government of India because of energy security and environmental issues. Renewable energy based power generation are being promoted instead in this region.

Power generation by Solar Photovoltaic (PV) technology:

The figure 5.8 shows the layout of the system where only PV based electricity generation was considered. The software yielded optimised capacities of the components and various cost figures. HOMER suggested configuration is 79 kWp PV modules, 30 kW power converter and 360 numbers of battery of 800 Ah, 2 volt DC each. Associated total NPC is 637800 USD (425200) and levelised COE is 0.791 USD/kWh (0.53 Euros/kWh). The initial capital cost is 529700 USD (353150 Euros).

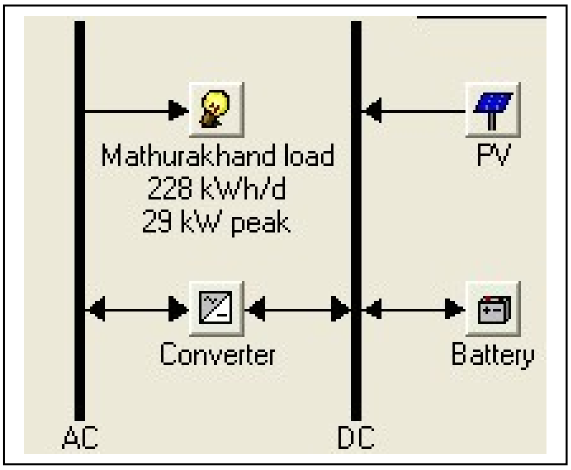


Fig 5.8: PV based energy generation

A PV array large enough to avoid capacity shortage in the cloudy part of the year is guaranteed to produce excess electricity in the sunny part of the year. In this case the suggested system would produce 137,891 kWh per year from PV array while the total consumption would be about 79,063 KWh per year leaving 20.7% as excess electricity. Utilising this surplus power into some useful application in water/ air heat load or dumping etc. was not considered in this study. This excess electricity phenomenon will be reduced in other scenarios when the system will be of hybrid type.

Power generation by biomass gasification technology:

The layout for the optimisation analysis is shown in Fig. 5.9 below.

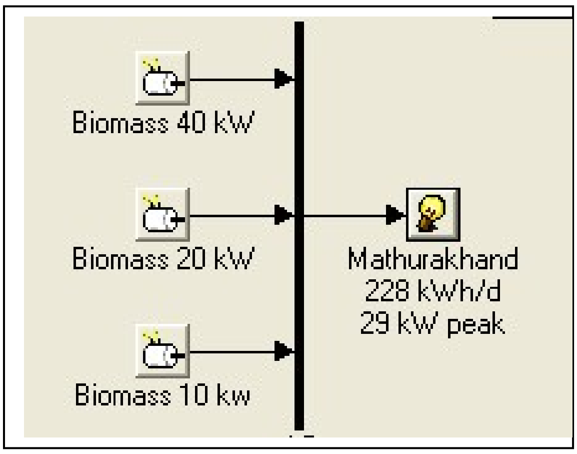


Fig 5.9: Layout considered for biomass optimization for Mathurakhand

The optimisation result is depicted in Table 5.3 below.

Table 5.3: Optimization result for gasification

bio40 (kW)	bio20 (kW)	bio10 (kW)	Initial Capital	Total NPC	COE ($/kWh)
	20	10	$ 45,000	$ 172,525	0.203
40			$ 50,000	$ 176,171	0.208
40		10	$ 70,000	$ 194,325	0.229
40	20		$ 75,000	$ 198,864	0.234
40	20	10	$ 95,000	$ 217,018	0.256

It can be seen that the suggested optimal system configuration is the simultaneous operation of two biomass gasifier, 20 kW and 10 kW respectively, incurring an NPC of 172525 USD (Euros 115000). This system would consume approximately 139075 kg of woody biomass per annum. It can be seen that in the prevailing price for woody biomass **a system with biomass resource looks very attractive** as far as the project cost values are concerned. However, deploying biomass based power station in a big scale in remote regions would provoke issues regarding sustainability of wood supply chain and ecological impacts etc. Moreover, the price of woody biomass is likely to change in the future depending on the demand – supply dynamics of the market. **Therefore, hybrid energy technology is being promoted** in Sundarbans.

Power generation by PV- biomass hybrid systems:

For optimisation, a PV – biomass hybrid system with a 20 kW biomass generator unit was analysed. The system layout is shown in Fig 5.10. The optimum configuration would consist of 12 kWp PV, 20 kW biomass, 30 kW power converter and 60 numbers of 800 Ah, 2 volt DC battery. The total NPC will be about 290282 USD (Euros 193500) while levelised COE will be in the tune of 0.359 USD/kWh (0.24 Euros/kWh). The initial capital cost will be about 152870 USD (101900 Euros). About 23% of the total energy production would come from solar electricity. The plant would consume approximately 121370 kg of woody biomass per annum. It is worth to be noted here that the excess electricity will be reduced to an amount of 5% only.

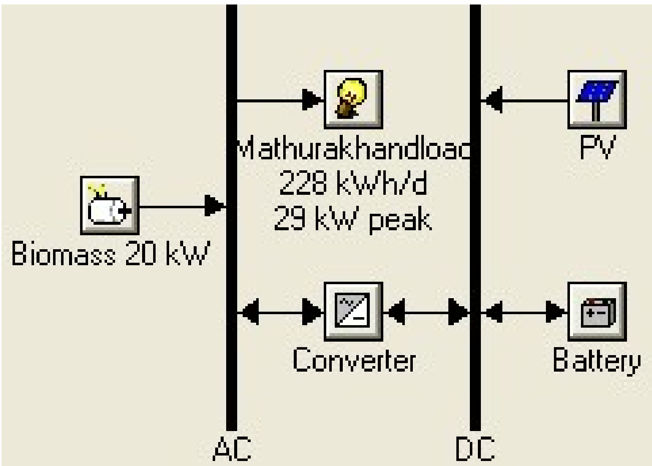


Fig 5.10: PV-biomass hybrid system

This pv-biomass hybrid system was considered as the source of power supply and corresponding values related to electricity generation were taken into account in the latter stage where distribution layout was estimated to give shape a complete techno-economics of power system for the village Mathurakhand.

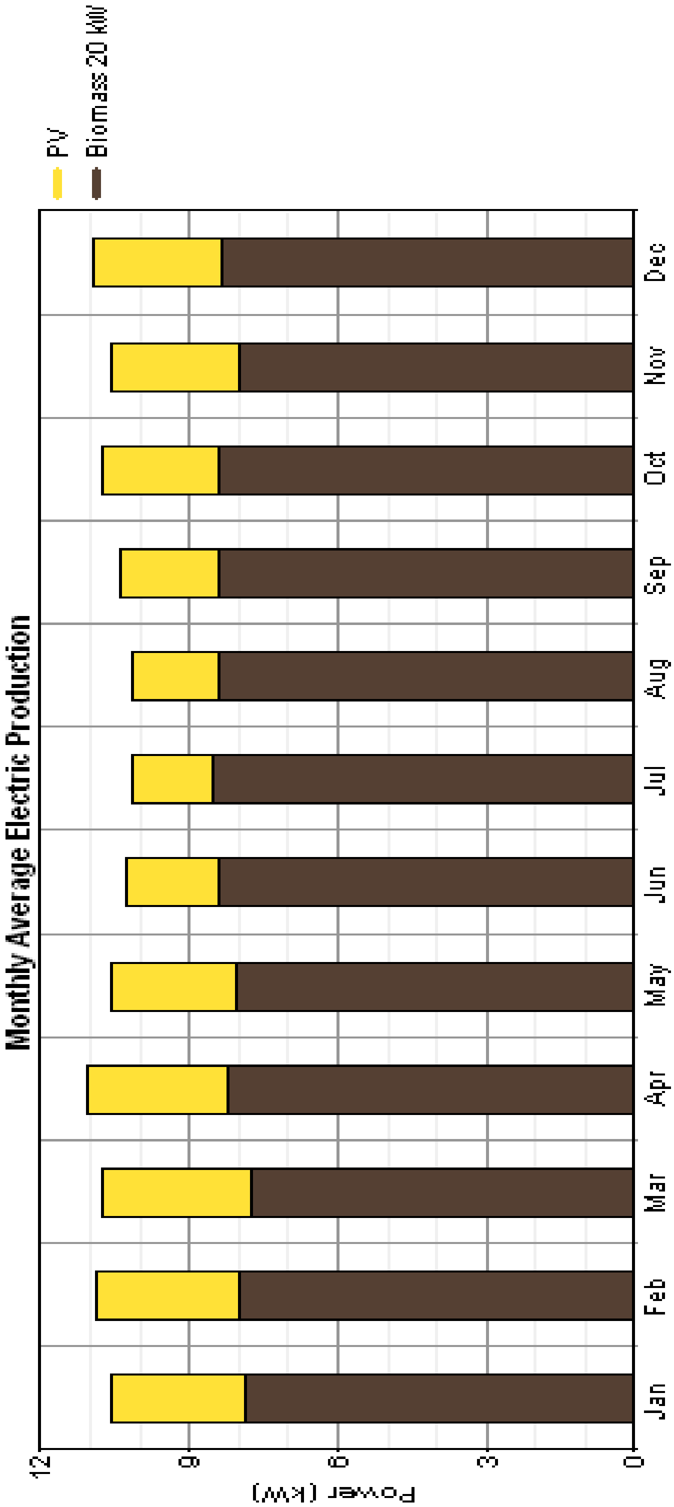


Fig 5.11: Monthly averaged electricity production

5.10.2 Results for the village Amlamethy

Baseline calculation by diesel power plant:

A diesel generating plant of 56.7 KW capacity was considered for the baseline case. For the 387 kWh per day annual average electricity demand for the village Mathurakhanda, the simulated system performance indicated that 141,255 kWh of electricity will be produced with a total net present cost (NPC) of 490163 USD (326800 Euros) and a levelised cost of energy (COE) production of 0.340 USD per kWh (0.23 Euros/kWh). The initial capital cost will be around 9000 USD (Euros 6000). Total diesel oil usage would be in the tune of 48560 litres per year contributing to annual emissions like 127,870 kg carbon dioxide, 315 kg carbon monoxide, 260 kg sulphur dioxide, 2,815 kg nitrogen oxides etc.

Power generation by Solar Photovoltaic (PV) technology:

HOMER suggested configuration is 135 kWp PV modules, 60 kW power converter and 600 numbers of battery of 800 Ah, 2 volt DC each. Associated total NPC is 1082200 USD (721500 Euros) and levelised COE is 0.791 USD/kWh (0.53 Euros/kWh). The initial capital cost is 917900 USD (611900 Euros). PV array field would produce 235,637 kWh per year while 134,195 kWh would be consumed leaving 21.2 % as excess electricity.

Power generation by biomass gasification technology:

The layout for the optimisation analysis is shown in Fig. 5.12 below. The optimal system configuration is the simultaneous operation of two biomass gasifiesr, 40 kW and 10 kW respectively, incurring initial capital cost of 70000 USD (46666 Euros), an NPC of 250300 USD (166850 Euros) and COE of 0.174 USD/kWh (0.12 Euros/kWh). This system would consume approximately 248600 kg of woody biomass per annum.

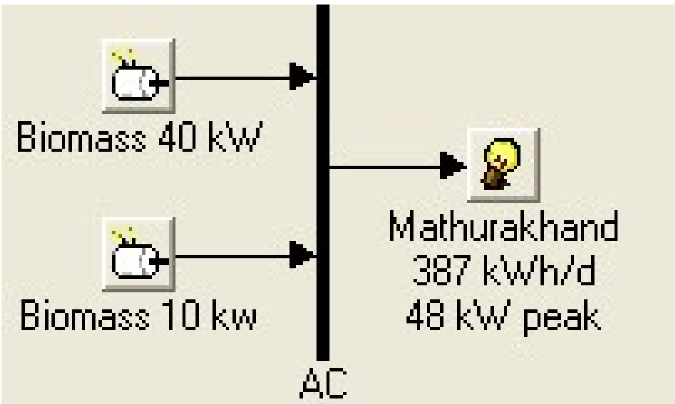


Fig 5.12: layout for biomass energy generation for Amlamethy

Power generation by PV- biomass hybrid systems:

For optimisation, a PV – biomass hybrid system with two biomass units, 10 kW and 20 kW respectively, were considered. The optimum configuration would consist of PV-53 kWp, biomass-10 kW+20 kW, power converter-30 kW and 240 numbers of 800 Ah, 2 volt DC battery. The total NPC will be about 582700 USD (388450 Euros) with initial capital cost of 418018 USD (278700 Euros) while levelised COE will be about 0.426 USD/kWh (0.28 Euros/kWh).

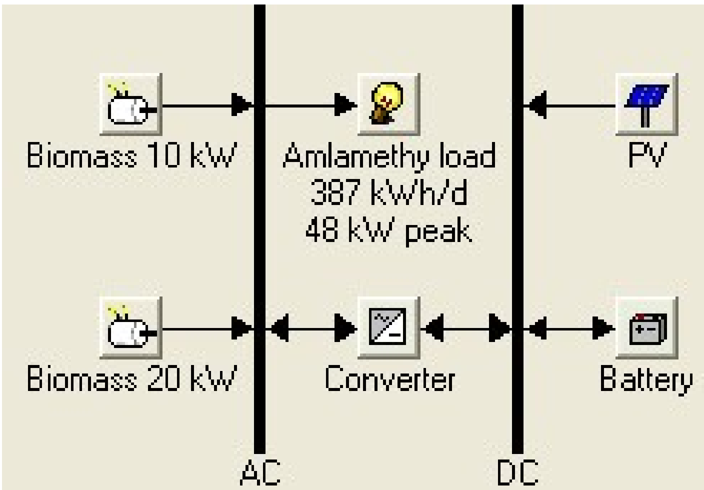


Fig 5.13: Optimization layout considered for Amlamethy PV-biomass plant

About 56% of the total electricity will be produced from the PV component. 121600 kg of woody biomass would have to be used per year in order to operate the biomass units.

5.10.3 Results for a central plant serving both Mathurakhand and Amlamethy

Aggregate load profile

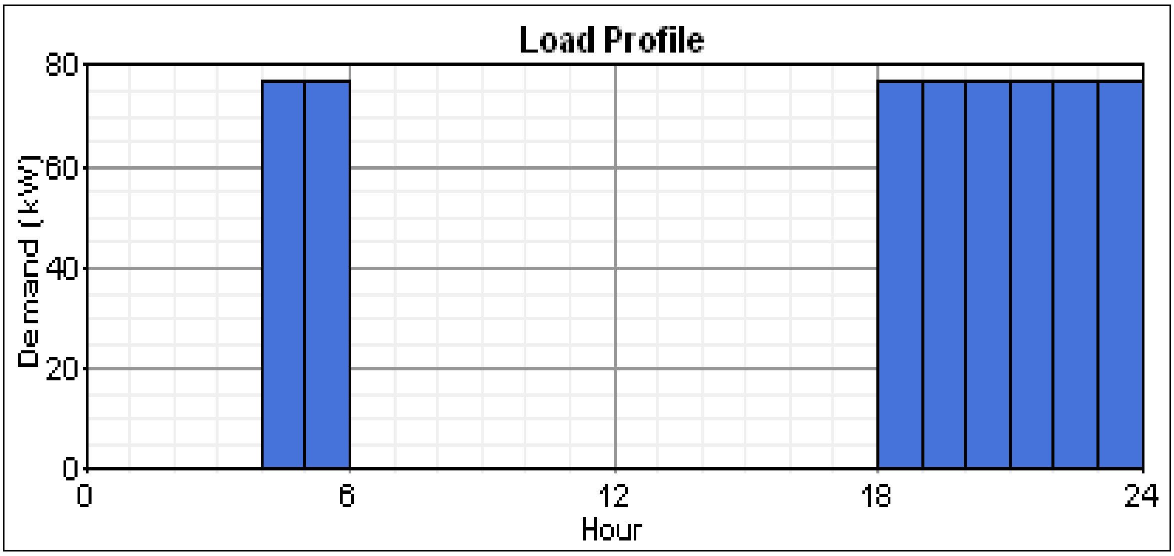


Fig 5.14: Aggregate load profile

Baseline calculation by diesel power plant:

Two diesel generating units of 56.7 kW and 30 kW capacities respectively were considered for the baseline case. For the 615 kWh per day annual average electricity demand for the central system, the simulated system performances are shown in the figures 5.15 and 5.16 and table 5.4.

Table 5.4: economic performance result

Initial capital (USD)	16125
NPC (USD)	764950
Operating cost (USD/year)	73450
Diesel consumption (L/year)	76370
COE (USD/kWh)	0.334

Production	kWh/yr	%
Diesel 56.7 kW	165,569	74
Diesel 30 kW	58,913	26
Total	224,481	100

Consumption	kWh/yr	%
AC primary load	224,475	100
Total	224,475	100

Fig 5.15: Generation statistics

Pollutant	Emissions (kg/yr)
Carbon dioxide	201,110
Carbon monoxide	496
Unburned hydrocarbons	55
Particulate matter	37.4
Sulfur dioxide	404
Nitrogen oxides	4,430

Fig 5.16: Emission from Diesel plant

Power generation by Solar Photovoltaic (PV) technology:

The final configuration is 220 kWp PV modules, 90 kW power converter and 900 numbers of battery of 800 Ah, 2 volt DC each. Associated total NPC is 1693800 USD (1129200 Euros) and levelised COE is 0.779 USD/kWh (0.52 Euros/kWh). The initial capital cost is 1465350 USD (976900 Euros). PV array field would produce 384,001kWh per year leaving 23.2 % as excess electricity.

Power generation by biomass gasification technology:

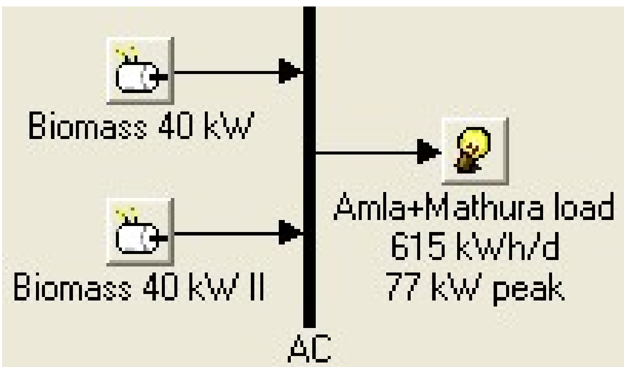


Fig 5.17: Biomass units considered for analysis

For the aggregate load of 615 kWh per day the plant would produce 224475 kWh of electricity per year by using approximately 399575 kg of woody biomass. Corresponding initial capital cost would be 100000 USD (66666 Euros) incurring a total NPC of 348700 USD (232460 Euros) and COE of 0.152 USD/kWh (0.1 Euros/kWh).

Power generation by PV- biomass hybrid systems:

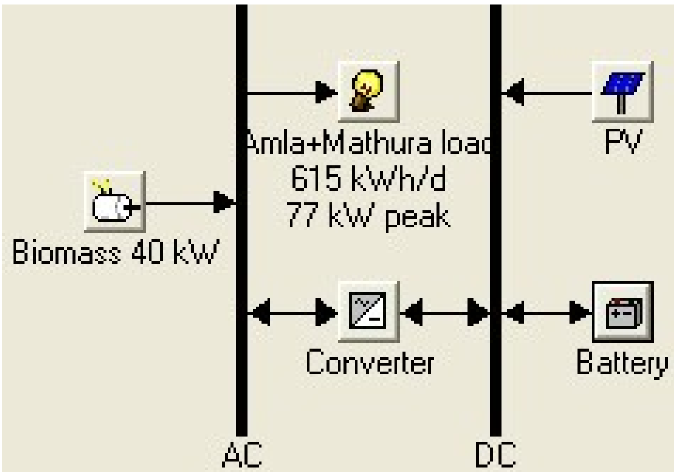


Fig 5.18: Layout for optimizing PV-biomass plant

The optimum configuration would consist of PV-67 kWp, biomass-40 kW, power converter-60 kW and 420 numbers of 800 Ah, 2 volt DC battery. The total NPC will be about 862300 USD (574870 Euros) with initial capital cost of 586200 USD (390800 Euros) while levelised COE will be about 0.392 USD/kWh (0.26 Euros/kWh). About 45% of electricity would be produced from PV. There will be approximately 250120 kg / year of woody biomass consumption.

5.10.4 Results for distribution system

5.10.4.1 Mathurakhand without terrain features

PV-Biomass hybrid power station has been considered for generating source. Here the terrain features of land usage, roads, rivers, water bodies etc. were not taken into calculation. The locations of the power plants are taken arbitrarily in these calculations but kept constant throughout distribution system modeling. Here scenarios were built up where all houses get connected to the centralized system. Isolated systems like solar home systems were not considered in this study. ViPOR result suggested the following distribution line layout as depicted in Fig 5.19. Here the green points are households (demand points), blue lines are low voltage wires and red lines represent medium voltage distribution line. The yellow triangle represents the PV biomass power plant location. This system would have low voltage lines of total 7501 meters and medium voltage lines of total 10273 meters. There will be a total of 77 step-down transformers which are represented in the figure as red dots. The corresponding cost figures are depicted in Table 5.5. The levelised COE for electricity supply comes out to be 0.556 USD / kWh (0.37 Euros/kWh).

Table 5.5: Cost components in Mathurakhand power system without terrain consideration

Component	Net present cost (USD)	Initial capital cost (USD)	Total annualized cost (USD/year)
Energy generation	290282	152870	28474
Electricity distribution	196348	157397	17768
Total energy supply	486630	310267	46242
Per load	2134	1361	203

5.10.4.2 Mathurakhand with terrain features

In this case the differences in costs of distribution lines over road, agricultural land and water body were taken into account. The result suggested the following layout as depicted in Fig. 5.20. It can be seen that the route of this distribution scheme is not identical with the previous case where no considerations were made towards terrain / land usage related features. Consequently the cost figures of the electrification scheme are increased to incur a levelized COE supply of 0.649 USD per kWh (0.43 Euros/kWh). This scheme would have low voltage lines of total 4887 meters and medium voltage lines of total 12273 meters. There will be a total of 123 step-down transformers which are represented in the figure as red dots. The cost figures are shown in Table 5.6.

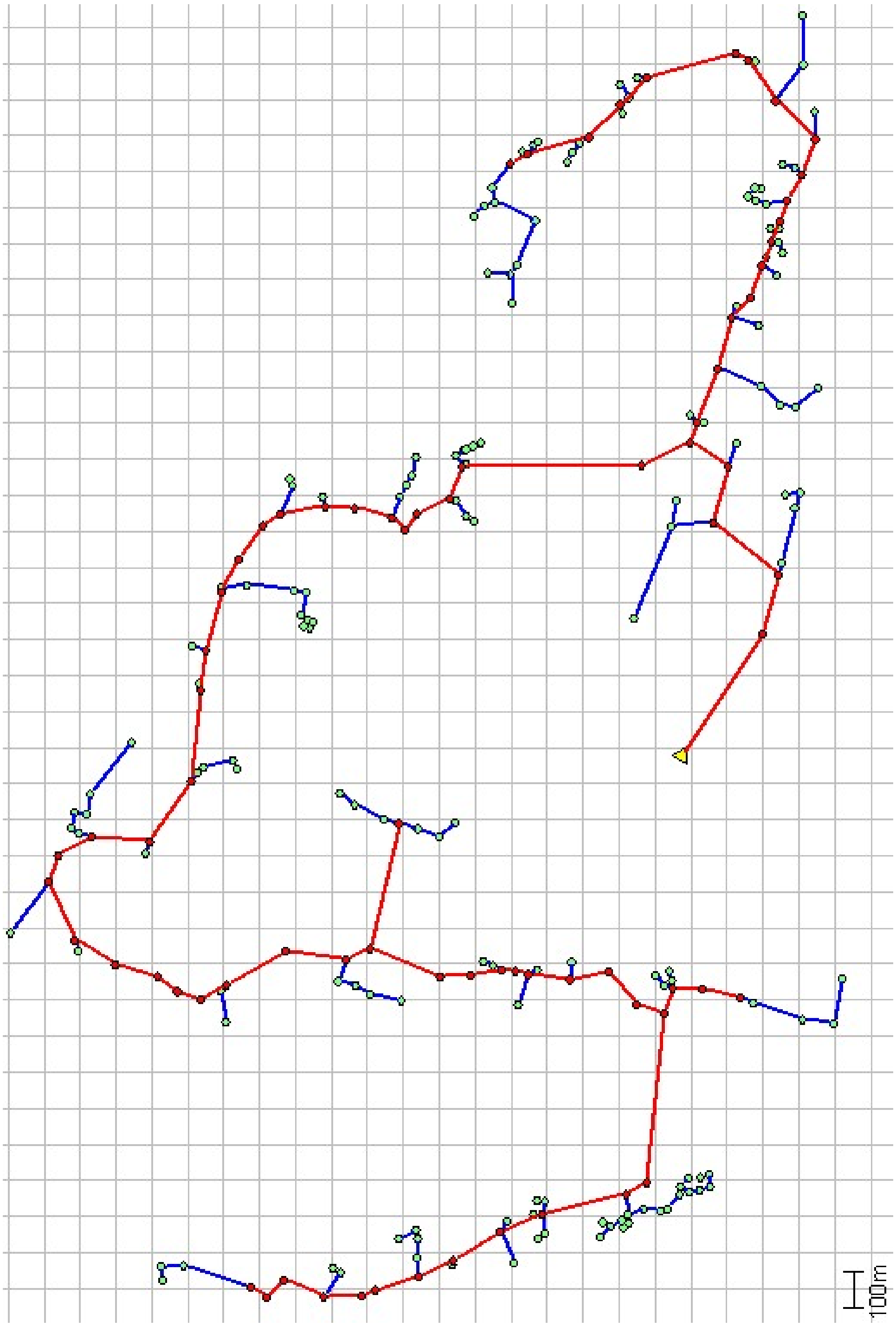


Fig 5.19: Mathurakhand power system layout without terrain consideration

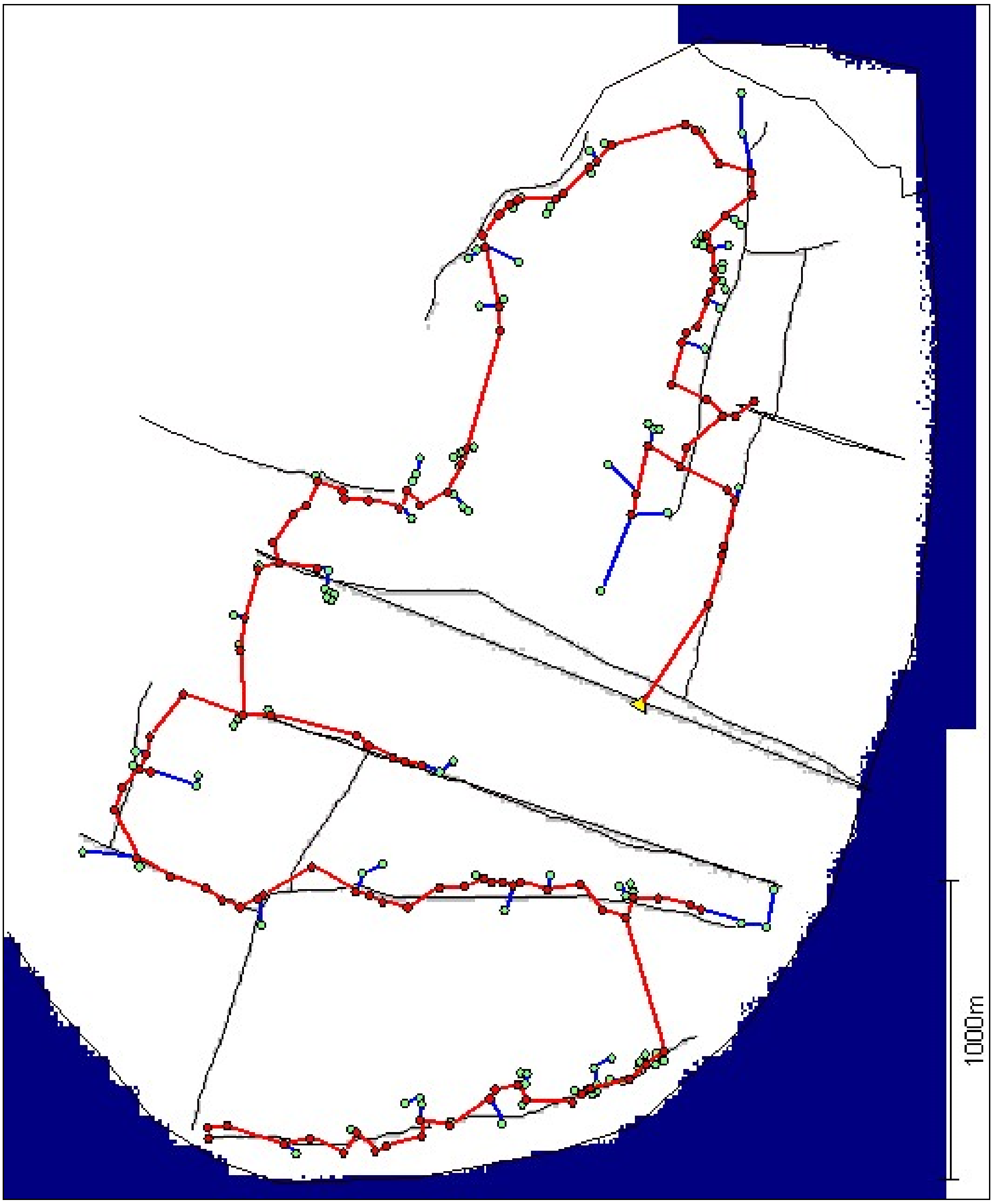


Fig 5.20: Mathurakhand power system layout with terrain consideration

Table 5.6: Cost components associated considering terrain

Component	Net present cost (USD)	Initial capital cost (USD)	Total annualized cost (USD/year)
Energy generation	290282	152870	28474
Electricity distribution	282107	228758	25554
Total energy supply	572389	381628	54028
Per load	2510	1674	237

5.10.4.3 Amlamethy without terrain features

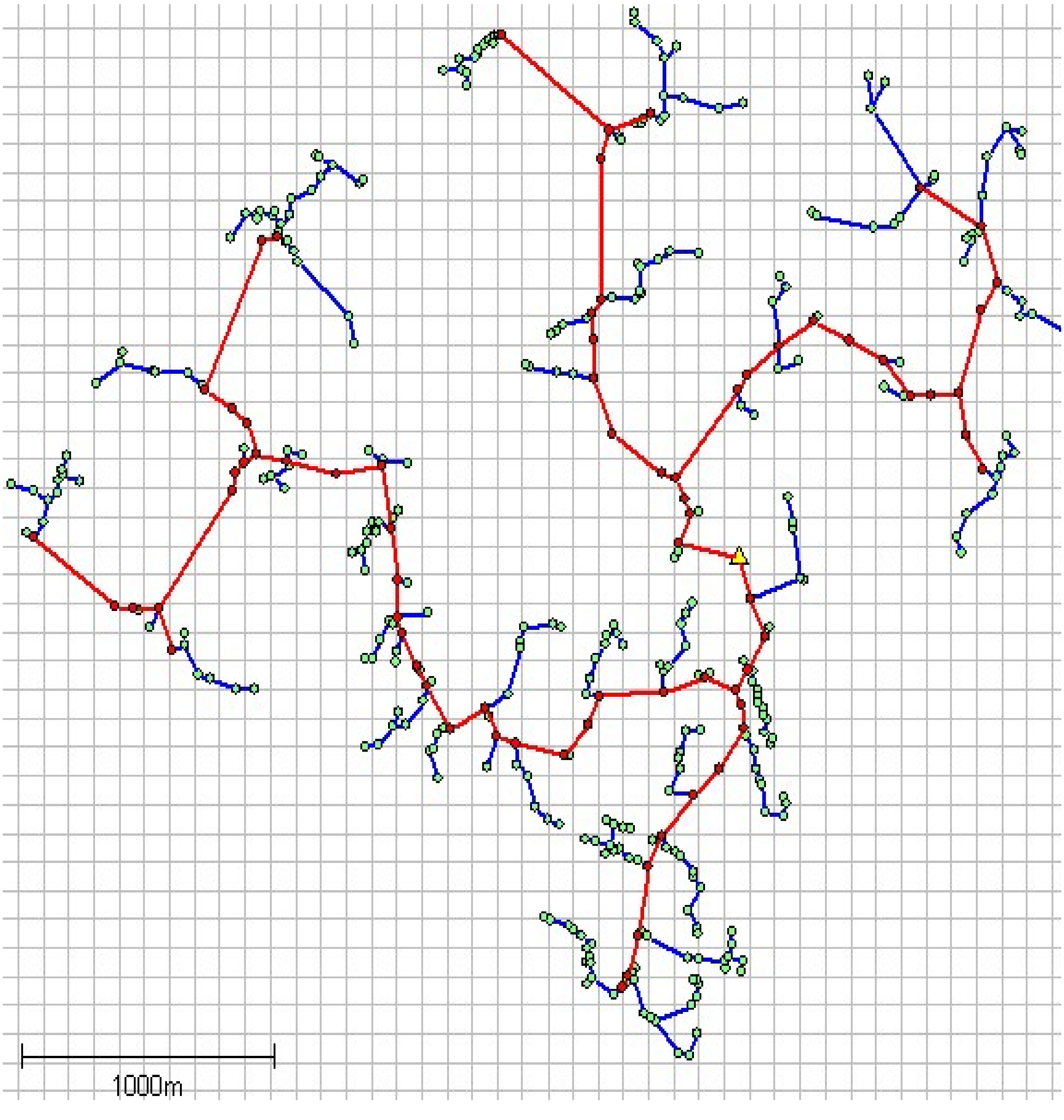


Fig 5.21: Amlamethy power system layout without considering terrain features

This system would have low voltage lines of total 17247 meters and medium voltage lines of total 12573 meters. There will be a total of 77 step-down transformers which are represented in the figure as red dots. The corresponding cost figures are depicted in Table 5.7. The levelised COE for electricity supply comes out to be 0.597 USD / kWh (0.4 Euros/kWh).

Table 5.7: Cost figures for Amlamethy power system

Component	Net present cost (USD)	Initial capital cost (USD)	Total annualized cost (USD/year)
Energy generation	582669	418018	57154
Electricity distribution	300668	234272	27127
Total energy supply	883336	652290	84281
Per load	2283	1686	218

5.10.4.4 Central plant without terrain features

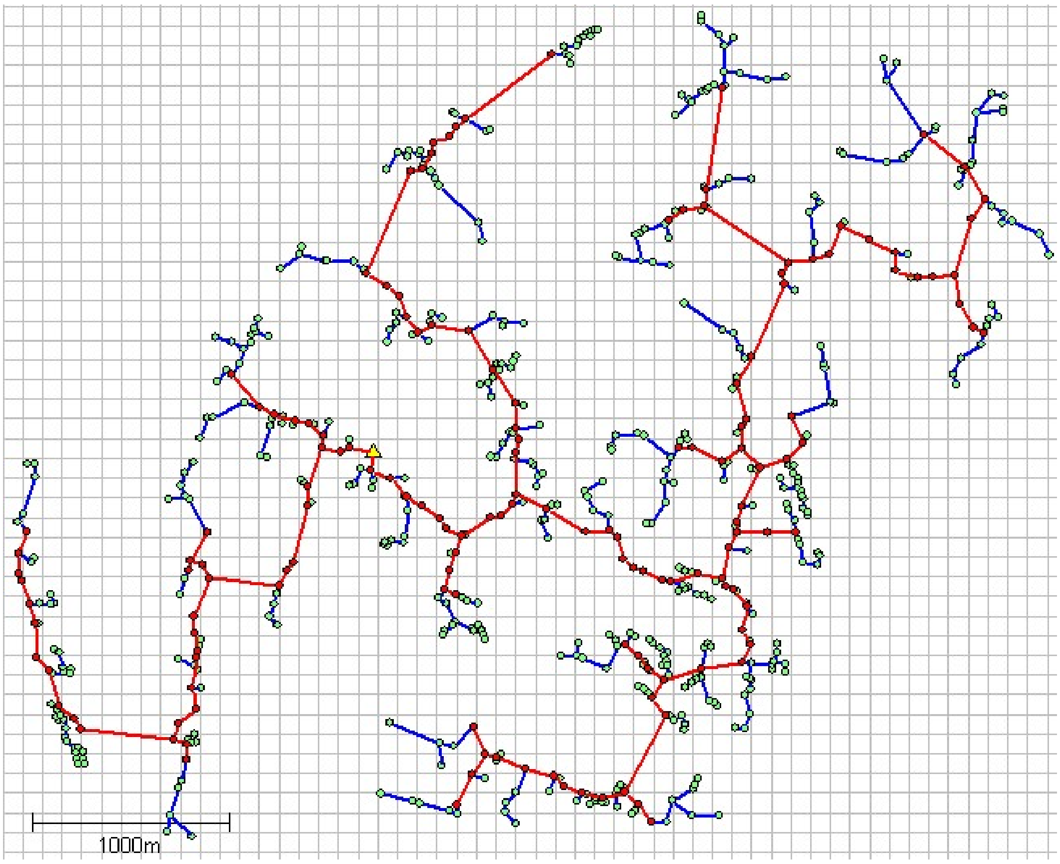


Fig 5.22: Central plant power system without terrain features

This system would have low voltage lines of total 25515 meters and medium voltage lines of total 20444 meters. There will be a total of 154 step-down transformers which are represented in the figure as red dots. The corresponding cost figures are depicted in Table 5.8. The levelised COE for electricity supply comes out to be 0.569 USD / kWh (0.38 Euros/kWh).

Table 5.8: Cost components for central system without terrain

Component	Net present cost (USD)	Initial capital cost (USD)	Total annualized cost (USD/year)
Energy generation	862325	586203	84587
Electricity distribution	477123	374511	43111
Total energy supply	1339447	960713	127698
Per load	2178	1562	208

5.10.4.5 Central plant with terrain features

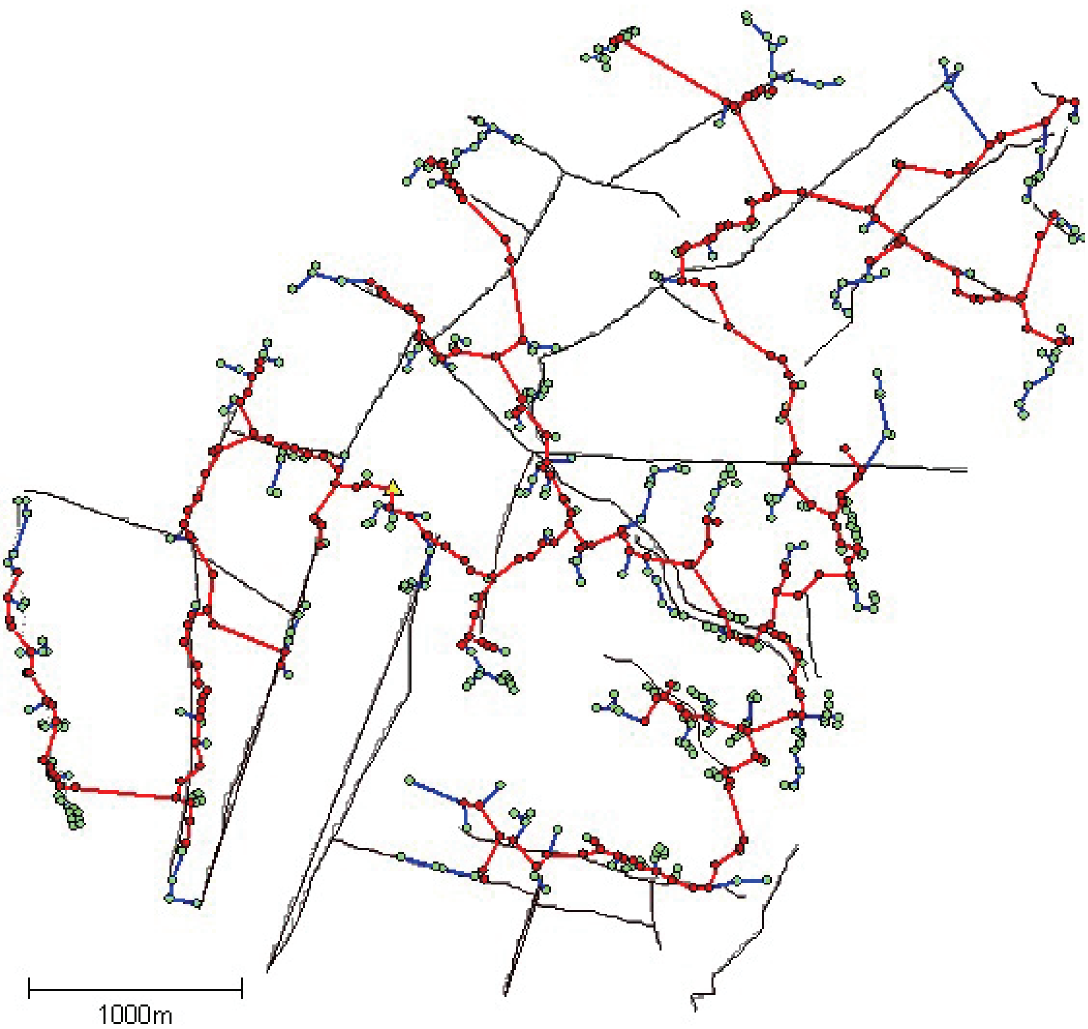


Fig 5.23: Central system considering terrain features

This system would have low voltage lines of total 19506 meters and medium voltage lines of total 24671 meters. There will be a total of 247 step-down transformers which are represented in the figure 5.23 as red dots. The corresponding cost figures are depicted in Table 5.9. The levelised COE for electricity supply comes out to be 0.652 USD / kWh (0.43 Euros/kWh).

Table 5.9: cost figures for central system considering terrain

Component	Net present cost (USD)	Initial capital cost (USD)	Total annualized cost (USD/year)
Energy generation	862325	586203	84587
Electricity distribution	682798	540636	61748
Total energy supply	1545123	1126838	146336
Per load	2512	1832	238

It is clear by now that the effect of the types of terrain and land usage are significant in power distribution layouts.

5.11 Phase 2: Ground validation for improving accuracy

In order to increase the accuracy of the case study, a dedicated ground survey was conducted with hand held GPS data recording instrument. In this survey the type of the loads were identified in terms of households, schools, market places etc. For each type of load, separate electricity demand calculations were made.

Schools: There are thirteen schools within the case study area. A visit was made to all of the schools. The schooling duration is from 10 AM to 4. 30 PM four days a week and till 1.30 PM on Saturdays. It was felt that during the school hours the need for electricity is very less. The main need could be lighting whereas the daylight hours and the availability of daylight is quite high over the region. As described in section 5.6.1, the solar resource is quite favorable. Even in the totally overcast days, the amount of diffuse radiation is high. As a part of the electrification process the schools will be connected with electric distribution lines of course, but the amount of energy consumption would be insignificant for the planning process. For very few occasion in a typical year, there will be usage of electricity. In the future the schools may utilize more electricity for specific purposes like operating laboratory equipments, computers, special audio visual aids etc which will ultimately call for special attention in terms of total consumption capacity and duration of usage. In this case study, no special considerations were taken for the schools.

However, there is one hostel for students' accommodation and there exists immediate need for electricity. There are 10 dormitory rooms where students live. It is estimated that 4 light bulbs and 4 small fans will be required per room. Corresponding load requirement is 1.4 kW with 8 hours consumption per day with similar load duration as in the normal households.

Markets: There are three market places within the case study area. Visits were made in all markets. It is estimated that at present the electricity need for each shop in the markets can be to the tune of 20 kWh per month with a supply of 5 hours per day in the evening. This amount of electricity demand corresponds to 133 Watt connected load per shop.

In the market place called "Satyanarayanpur Bazar", there are 40 shops with an estimated demand of 5.3 kW. "Raja Bazar" has 25 shops with 3.3 kW demand. The smallest market, "Brihaspatibarer Bazar", has 10 shops with a total demand of 1.3 kW.

Other considerations: The demand in the household sector is estimated considering 30 kWh / month consumption which itself is ambitious. Moreover, it is assumed to have a unity diversity factor in the overall demand profile. So, the demand profile in the case study is probably at the higher side. No considerations were made in this study to 'initiate' new kinds of energy usages like health service, electrical motor based business activities, water pumping or community loads etc. The value of load growth in terms of increase in the households in the immediate past within the case study area is negligible. The modular nature of RE plant has the advantage of easy capacity augmentation, if the load grows in the future. Thus, no special considerations were made here to account for load growth.

Final demand:

Ultimately in this case study the analysis is done for 609 households, 75 shops and 1 students' hostel. The estimated demand considering the assumptions mentioned above is shown in the fig 5.24.

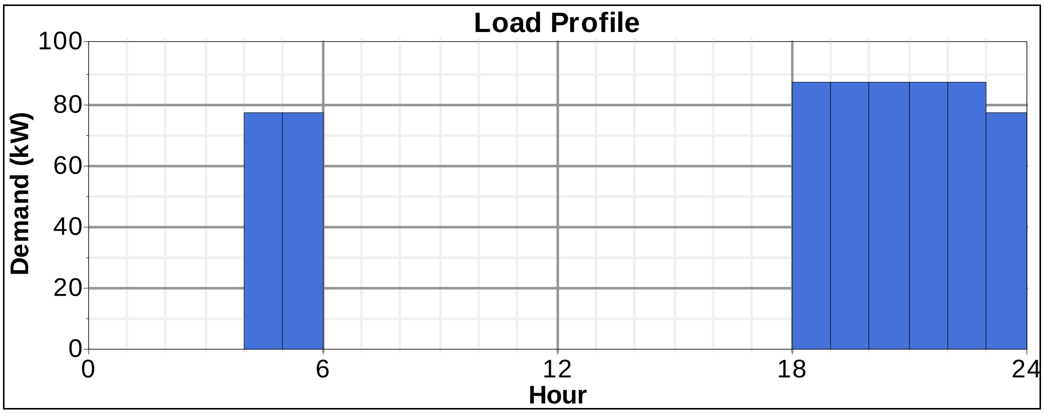


Fig 5.24: simplistic load profile for phase 2

This simplistic load profile repeats precisely day after day. In reality, the size and shape of the load profile will vary from day to day. In order to make this simplistic load profile slightly more realistic, an attempt has been made here where artificial randomness was added into the load profile. Keeping the fact in consideration that in other mini-grid plants of Sundarbans this load variation is very low in reality, very small amount of randomness is applied here. A daily random noise of 2% and hourly random noise of 3% were added to **create a synthetic demand profile** which produced a peak demand of 97.4 kW with annual average energy demand of 670 kWh/day with a corresponding load factor of 28.6%. This synthetically added demand profile is used for the calculations of stage 2 and is shown in the fig. 5.25. It can be seen the values of demand is not constant during 4-6 AM and 18-24 PM thorough out the year.

Power generation:

HOMER is used again to conduct simulation and optimisation exercises to arrive at the appropriate power generation option. Here PV-Biomass gasification hybrid system is considered with two biomass units of 40 kW and 10kW capacity. An effort is made to fine-tune the scheduling of the biomass units for improving the performance. An additional constraint of up to only 0.1% capacity shortage allowance is applied in the optimisation process. In addition, a value of 5%

operating reserve (also known as **spinning reserve** in traditional power system terminology) is applied as another constraint to account for a gross effect from distribution line loss, immediate short duration load growth in the market areas, safety factor in the planning etc. taken all together.

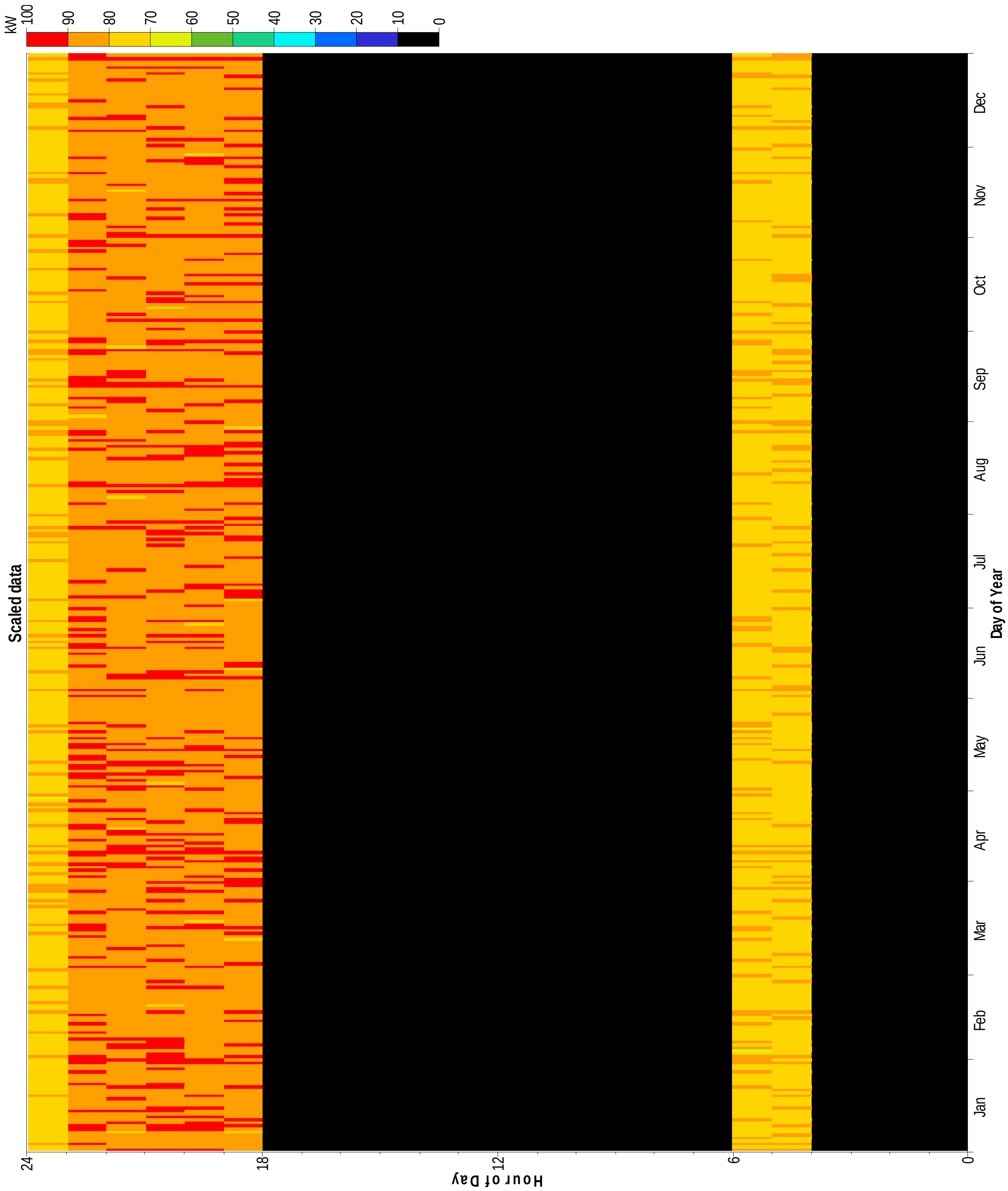


Fig 5.25: Profile of the electricity demand considered finally

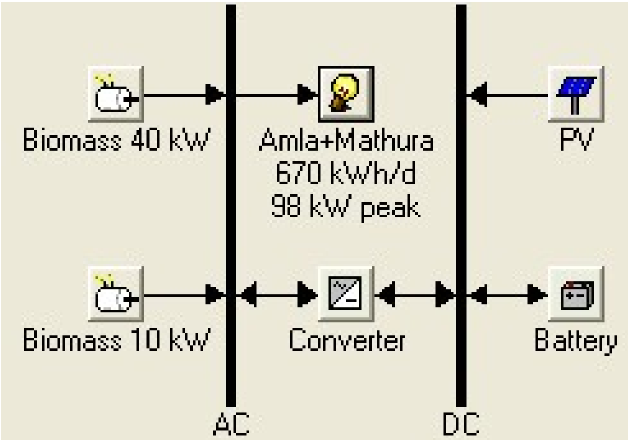


Fig 5.26: Layout for optimizing power plant in Phase 2

This time hourly time series analysis by HOMER produces a solution which would consist of 83 kWp PV, 540 numbers of 800 Ah, 2 volt battery, 60 kW power converter and 40+10 kW biomass units. The total NPC will be about 1034600 USD (689700 Euros) while levelized cost of generation will be 0.415 USD/kWh (0.28 Euros/kWh). The associated unmet load will be will be in the tune of 0.08% which is negligible for planning purpose. In fig 5.27 electricity generation of the plant is shown on monthly basis. This plant configuration is considered final and used in the next level of distribution calculation with ViPOR.

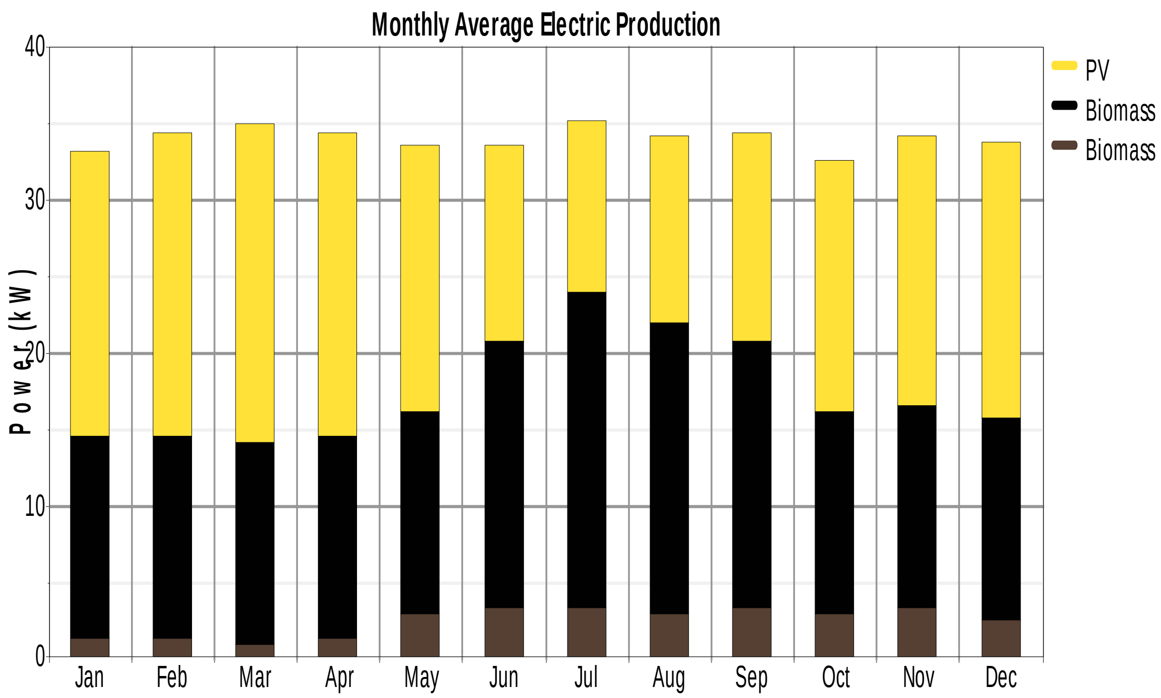


Fig 5.27: electricity generation by the plant

About 48% of electricity would be produced by PV while 44 % and 8% will come from Biomass 40 kW and 10 kW units respectively. Woody biomass consumption would to the tune of 271400 kg per year. Supplying the same load with a pure diesel generator plant would result in a levelized cost of energy production of 0.232 Euro/kWh (0.15 Euros/kWh) and would emit 230,775 kg/year CO_2, 570 kg / year CO, 460 kg/ year sulphur dioxide and 5000 kg/year nitrogen oxides. As stated in section 5.10.1, that pure biomass gasification based power system would have a lower cost of electricity generation than diesel plant. However, because of biomass resource availability issues, environmental concerns and government's policy in favour of promoting hybrid systems, PV-Biomass hybrid system is considered here. The simulated operation schedule of biomass units are depicted in fig. 5.28.

Battery Bank state of charge is shown in fig. 5.29. It will have about 25 hours of autonomy. The cost breaks up details are shown in fig. 5.30 for NPC and in fig. 5.31 for annualized costs. The overall graph of annual power generation is depicted in the fig. 5.32.

From these figures it is evident that in this type of project the maximum share of money is allocated for the capital costs and in this case the costs associated with the PV array. From the annual power graph it can be seen that the contribution from PV is less in the months of June to September. It is typical monsoon season there. It can also be seen that the optimisation is not theoretically perfect. There will be unmet load situations in the months of February, March, May and December only for total four days. However, the maximum capacity shortage will be only 0.1%. Considering the inherent lack of accuracy in the demand estimation process, this amount of theoretical shortage can be ignored in the planning process.

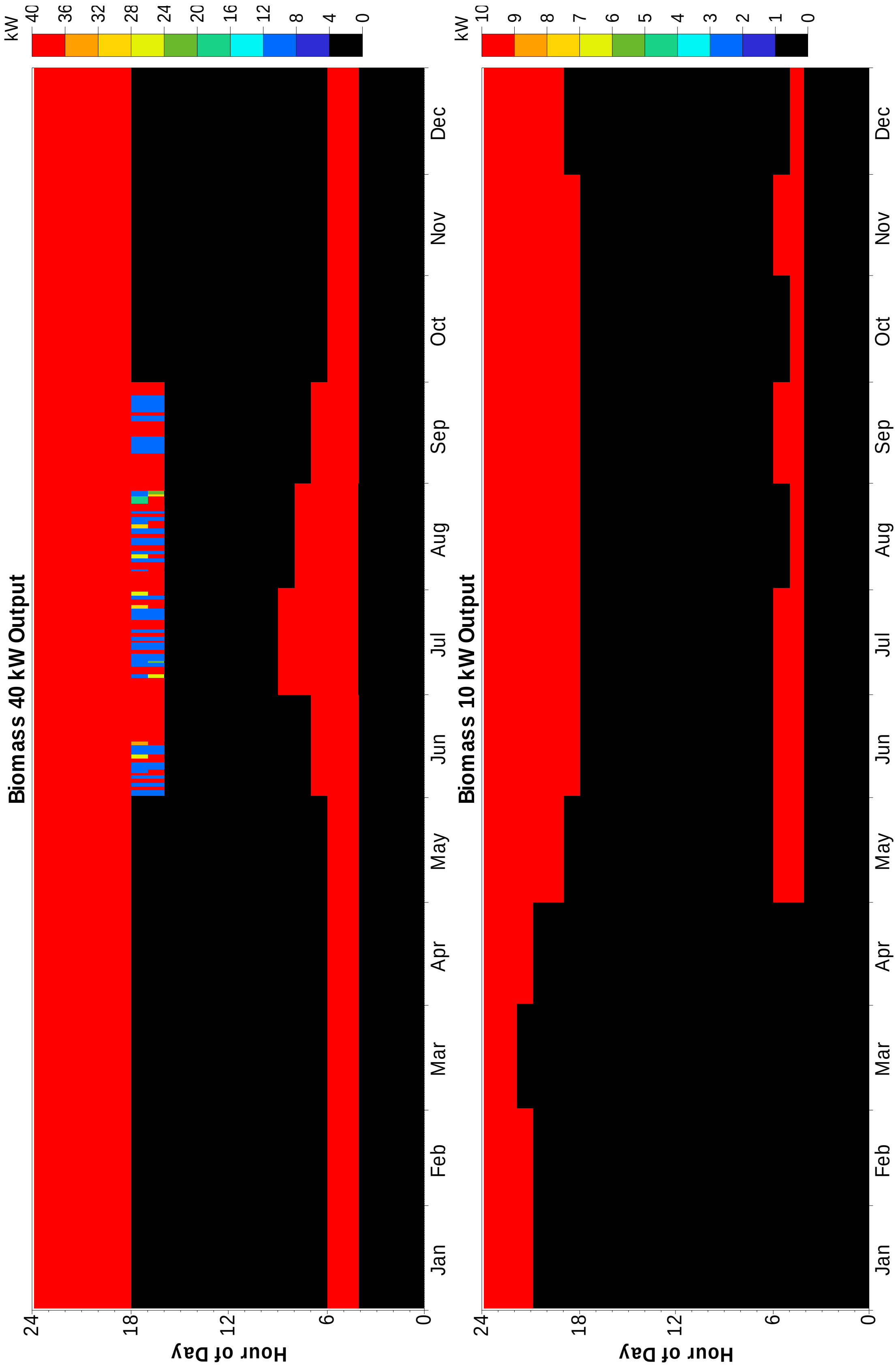


Fig 5.28: Biomass gasification based electricity generation schedule

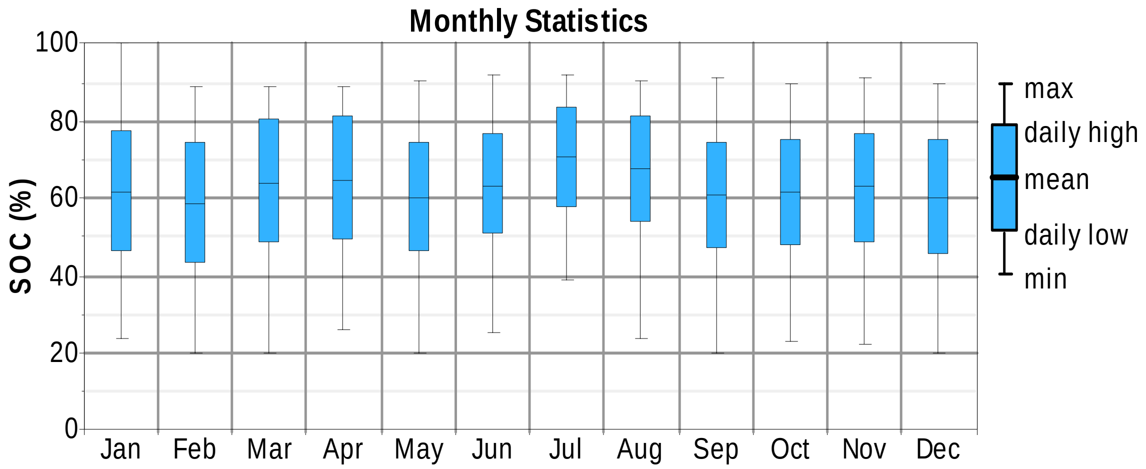
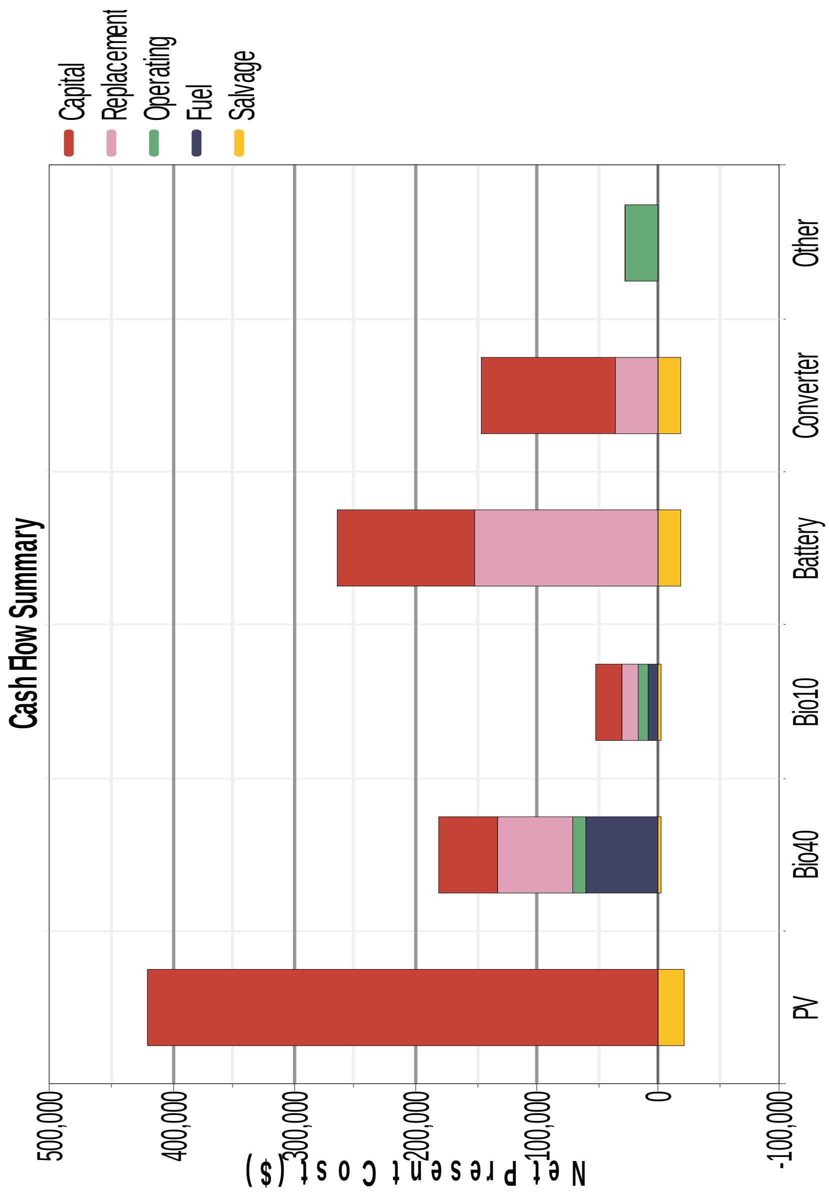


Fig 5.29: Battery Bank state of charge



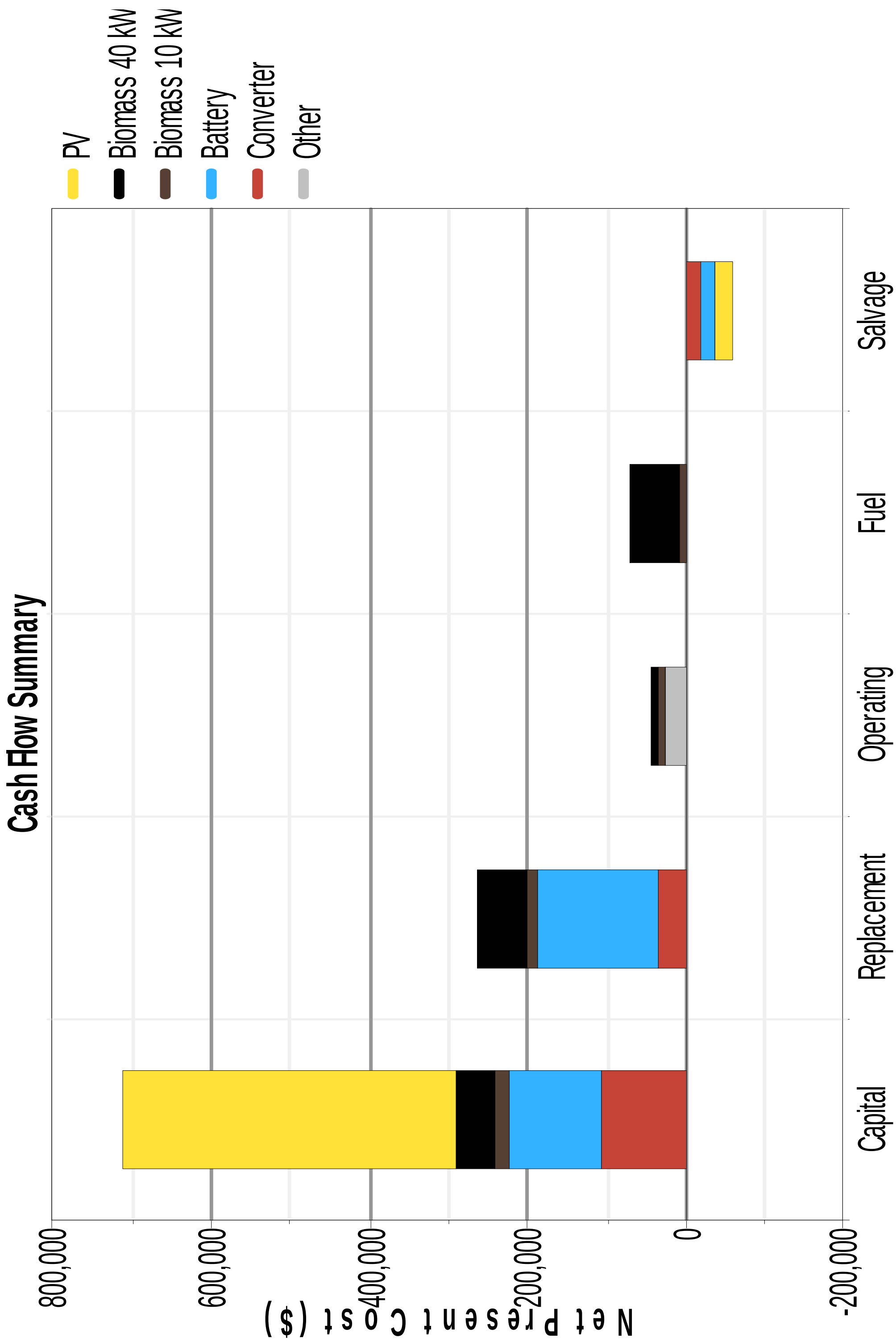
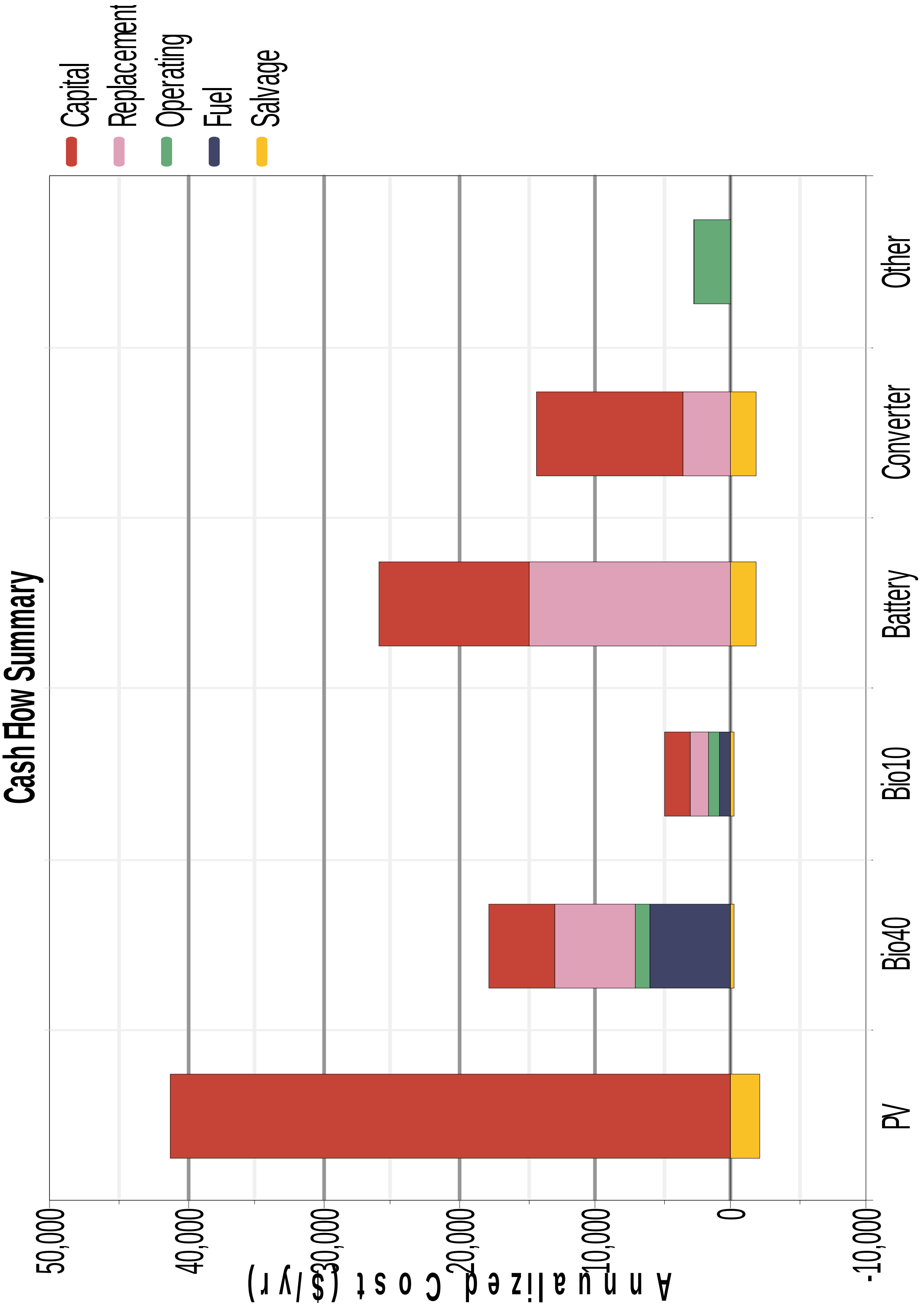


Fig 5.30: Net present costs of power plant


Cash Flow Summary
Capital
Replacement
Operating
Fuel
Salvage
50,000
40,000
30,000
20,000
10,000
0
-10,000
Annualized Cost ($/yr)
PV
Bio40
Bio10
Battery
Converter
Other

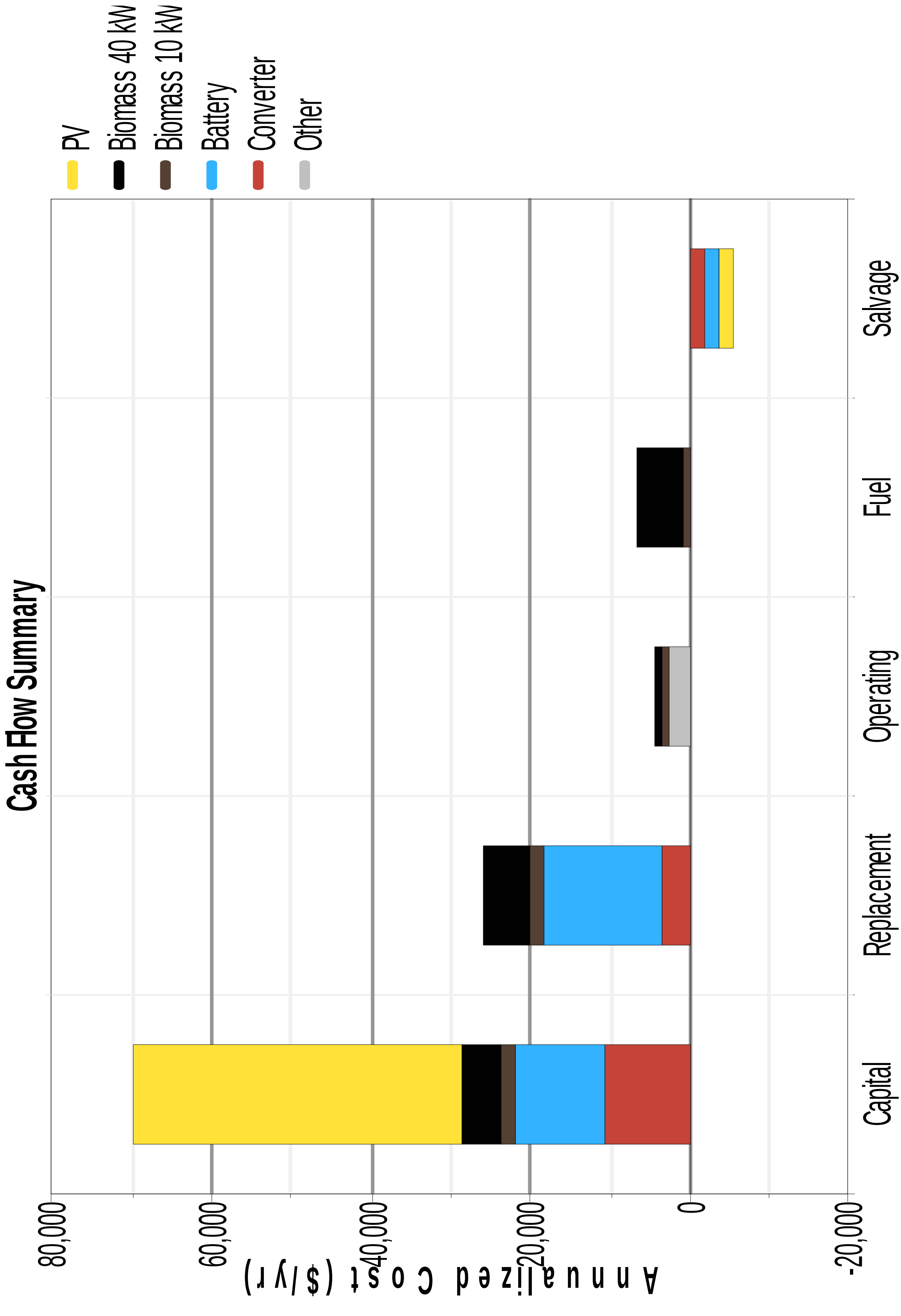


Fig 5.31: Annualized costs of Power plant

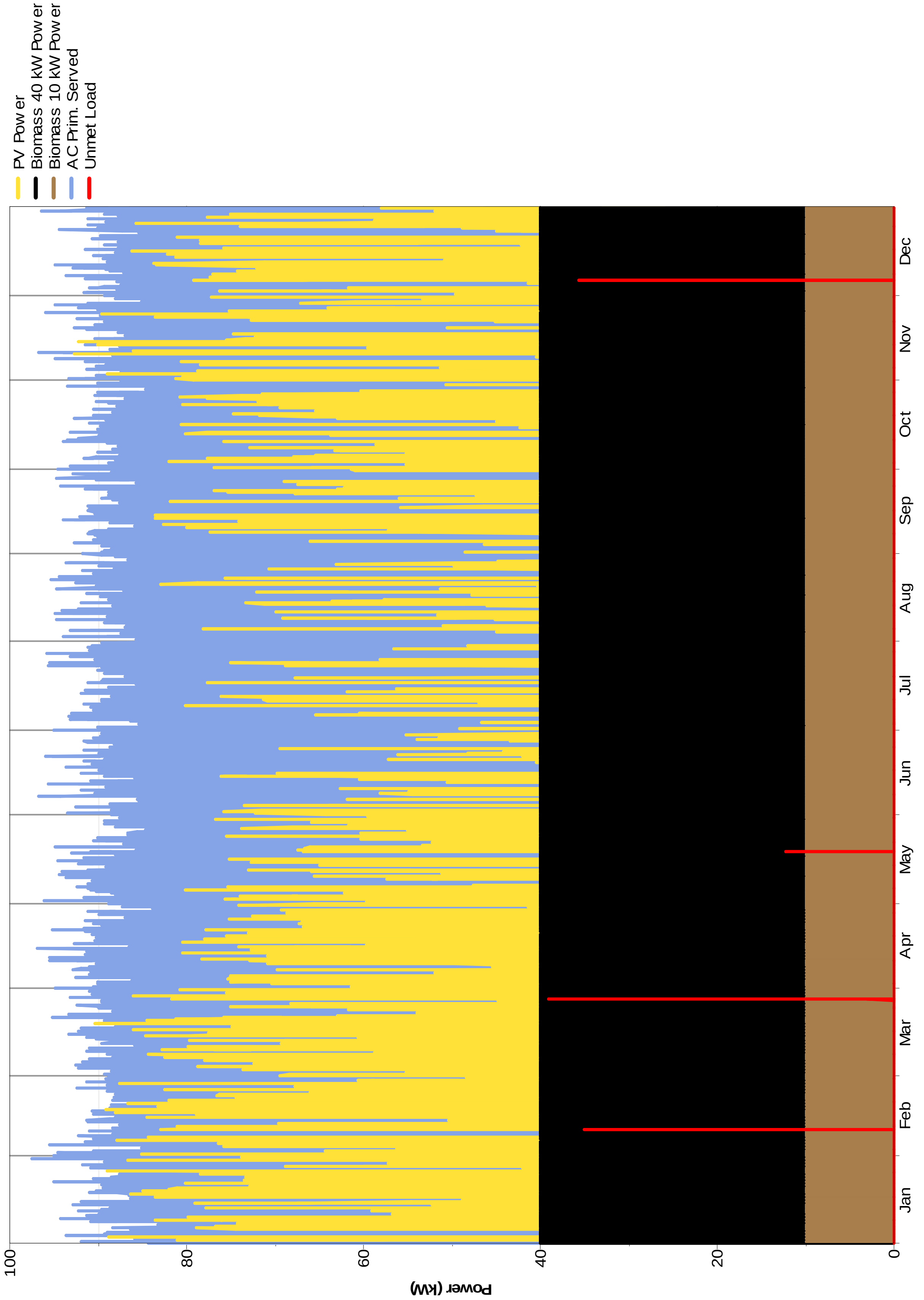


Fig 5.32: annual power generation graph

Power Distribution

Now, a fresh ViPOR analysis was made considering the finalized and modified load types and associated optimised power generation costs. The terrain features were included in the analysis and were kept identical with section 5.10.4.5. The final layout of the power supply is shown in the figure 5.34. The yellow points are shops in the market places. Only one blue point shows the location of the hostel. Green points are as usual represent the household load locations, red lines the medium voltage overhead lines and blue lines the low voltage lines..

This system would have low voltage lines of total 21661 meters and medium voltage lines of total 23848 meters. There will be a total of 216 step-down transformers which are represented in the figure as red dots. The corresponding cost figures are depicted in Table 5.10. The levelised COE for electricity supply comes out to be 0.668 USD / kWh (0.44 Euros/kWh).

Table 5.10: cost figures for final power system

Component	**Net present cost (USD)**	**Initial capital cost (USD)**	**Total annualized cost (USD/year)**
Energy generation	1034604	712319	101487
Electricity distribution	685389	540100	61919
Total energy supply	1719993	1252419	163406

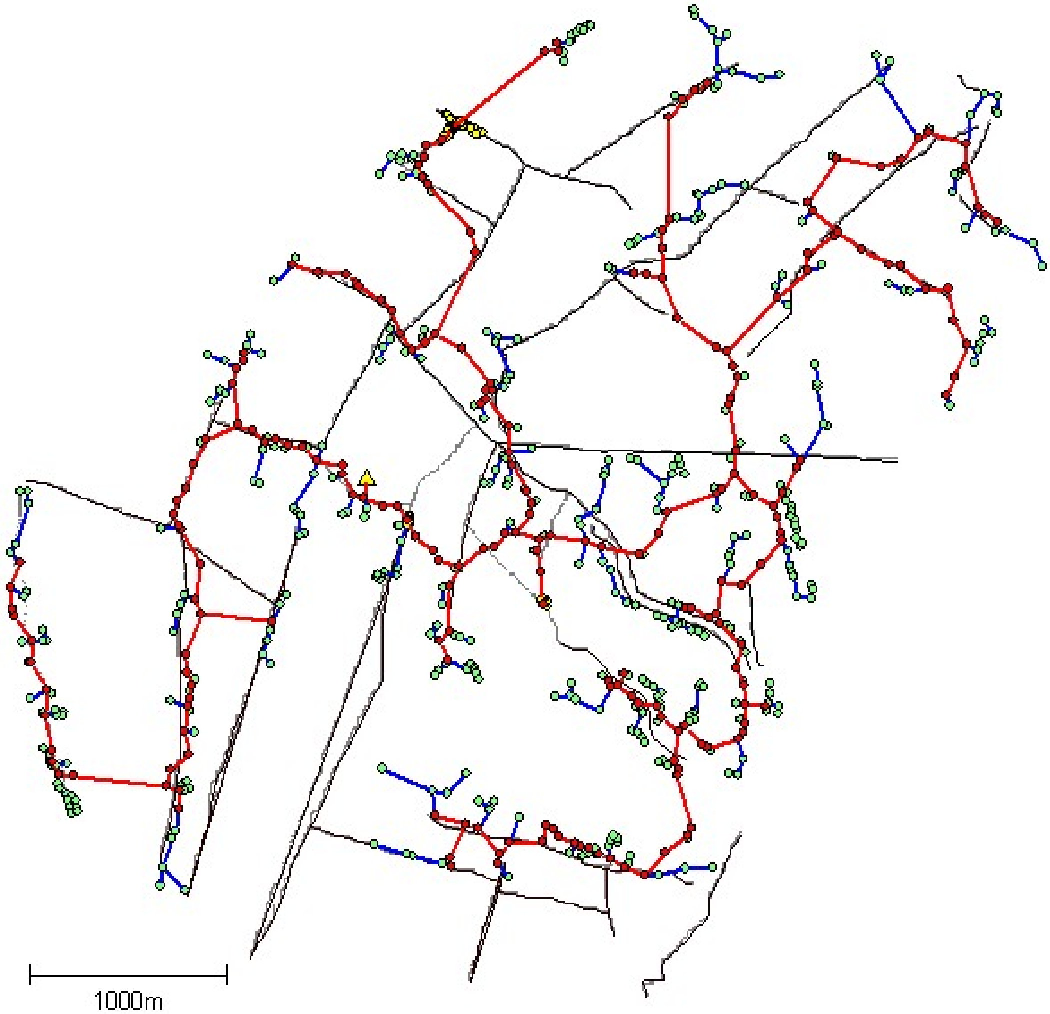


Fig 5.33: Final power system layout

5.12 Results of Phase 3: The impact of selected factors on electrification system of Phase 1

(A) Effect of load factor in power generation economics:

A simulation exercise has been conducted for the village mathurakhand with biomass gasification based power generation, as in section 5.10.1. Here the plant generation duration is varied in order to create different load factor scenarios. The result is depicted in fig. 5.34. The COE is decreasing with increase in the load factor. The black line is the best fit curve. The actual load factor was 33.3% only in Phase 1 analysis. This shows that by increasing usage duration (preferably innovating productive usage of energy) for electricity service the overall economics can be improved in the future.

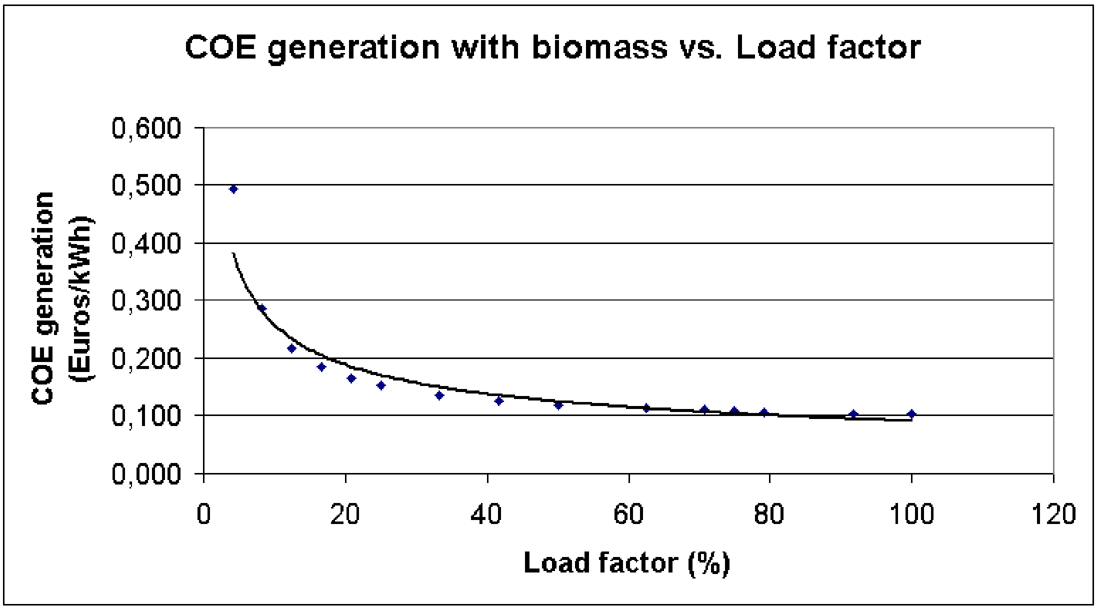


Fig. 5.34: Effect of load factor on levelised cost of biomass energy generation

(B) Effect of economic parameters

(1) Impact of the change in rate of interest

For Mathurakhand biomass- PV hybrid: A sensitivity analysis has been conducted with the changing rate of interest (discount rate). The result is shown in the fig. 5.35. However, it is inappropriate to compare projects with different discount rates. The discount rate is a property of the overall financial environment and not a property of the project.

High discount rates cause technologies like diesels with low capital costs and high long term costs to look better and low discount rates make renewable technologies look better.

The annualization formula is using the discount rate to convert today's capital cost into a cost that is spread out over future years in the project life, while the NPC formula is using the discount rate to convert future costs into a present cost. Increasing the discount rates increases the annualized costs (and therefore higher levelised COE) just like a higher interest rate will make a mortgage or other loan payment bigger. However, the Net Present Cost is just the sum of the initial capital cost plus all of the discounted future costs. The more one discounts those future costs the lower the NPC will become.

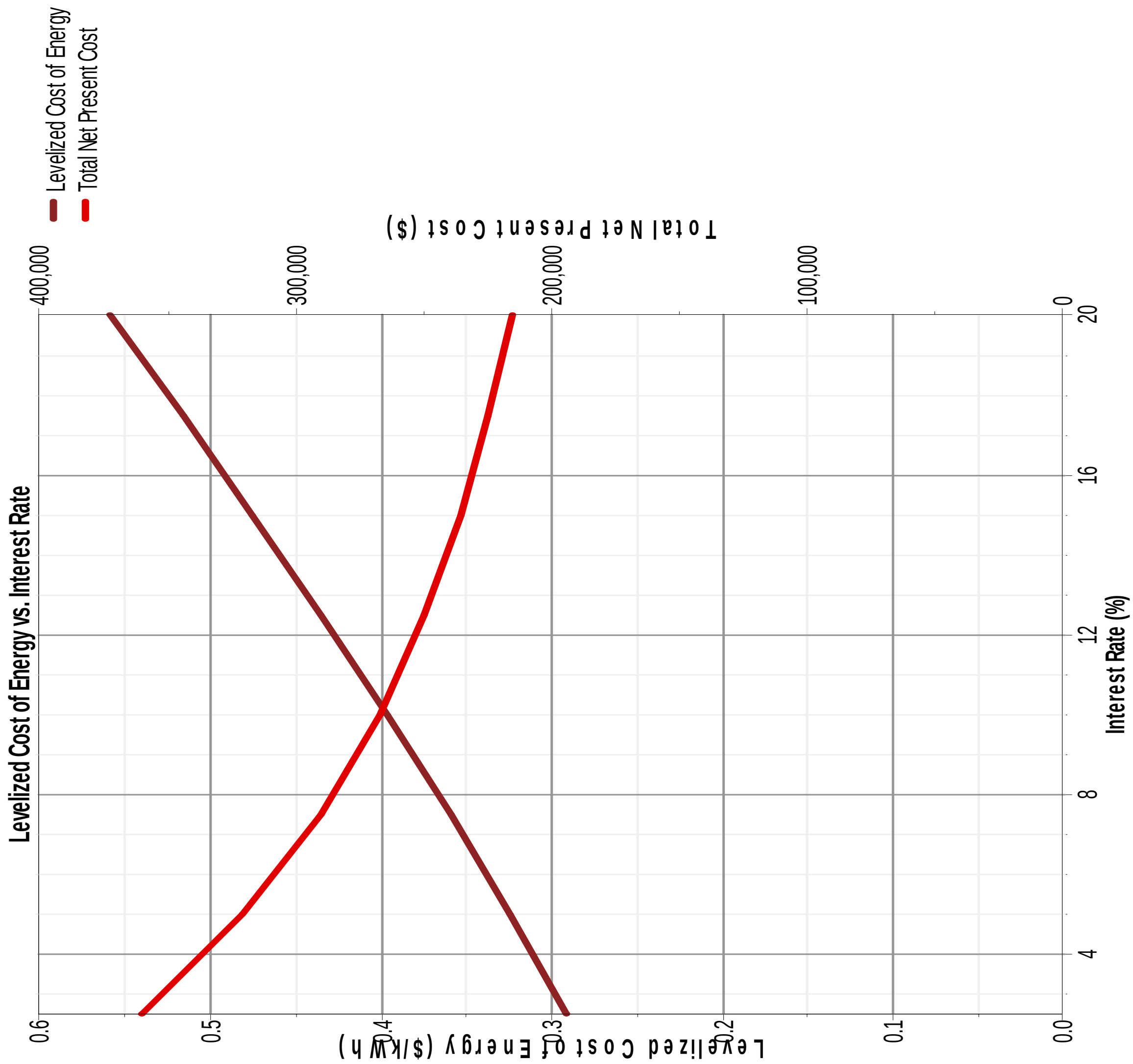


Fig 5.35: The effect of change in discount rates

(2) Impact of change in project life

For Mathurakhand biomass-PV hybrid: The sensitivity analysis result, as shown in the fig. 5.36, clearly depicts the importance of carefully estimate the project life in the overall techno-economic evaluation of island electrification projects. The importance remains equally crucial in the case of allocating life times for each components of the project, in the overall techno-economic performance.

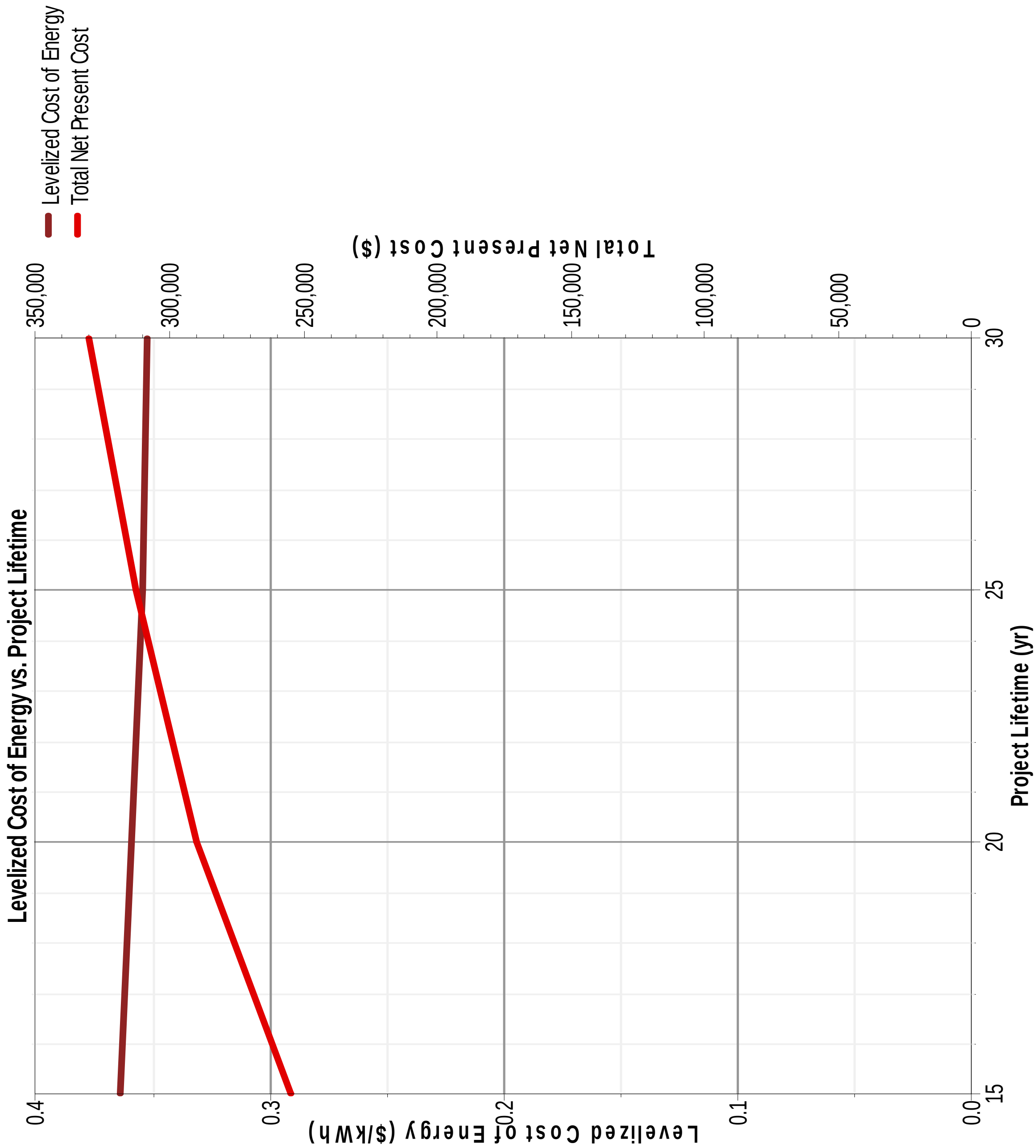


Fig 5.36: The effect of changing project lifetime

(C) Effect of changing fuel cost

For Mathurakhand:

(1) Diesel based power supply

The sensitivity result is shown in the fig. 5.37.

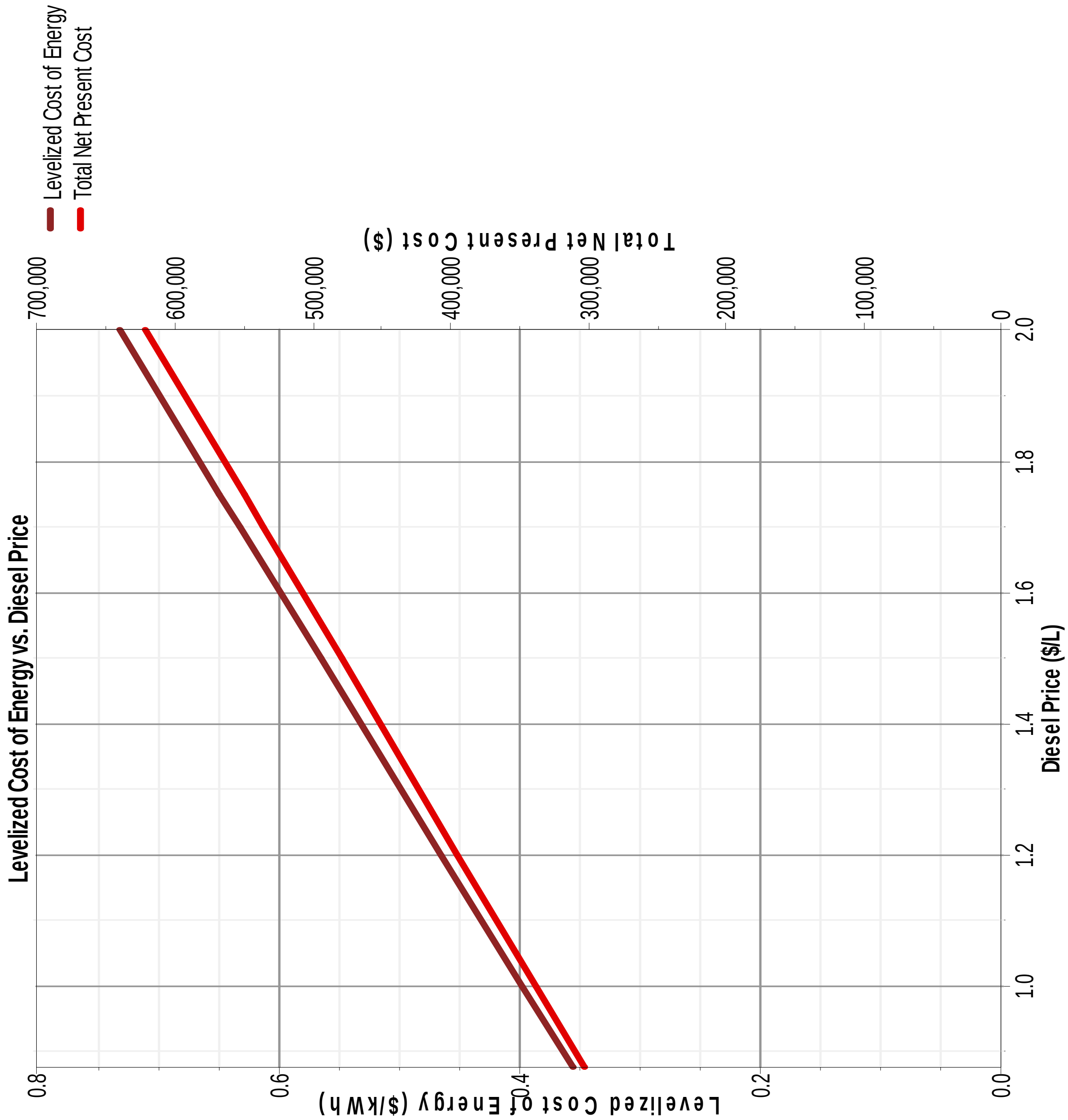


Fig 5.37: The effect of change in diesel price

(2) Change in price of biomass

The sensitivity result is depicted in the fig. 5. 38.

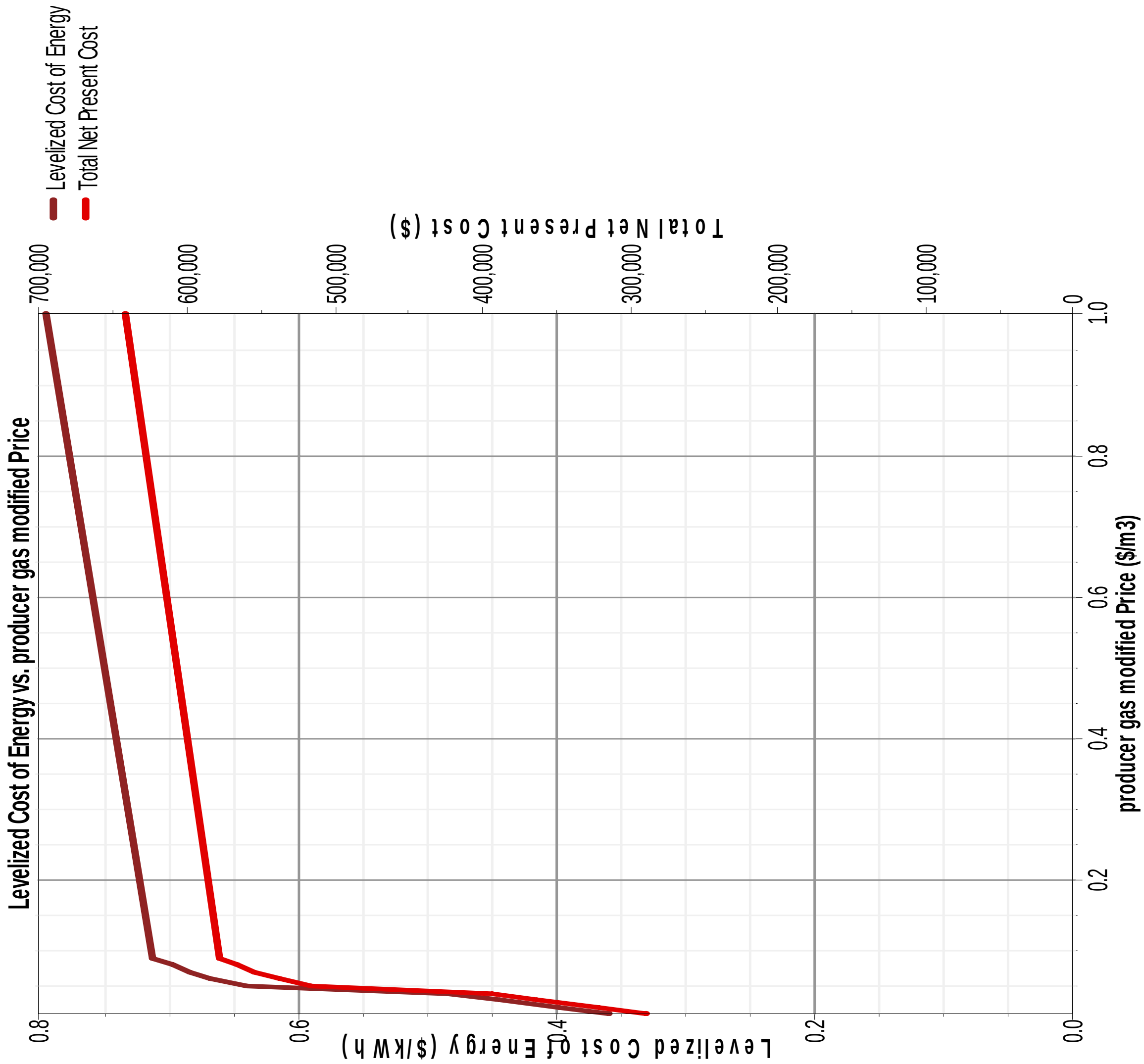


Fig 5.38: The effect of change in biomass price

(3) Choice of optimum system depends on fuel price

An optimization-sensitivity exercise has been conducted for Mathurakand.

The result is shown in the fig. 5.39. It can be seen that the optimal system configuration decision among biomass only, PV only and PV-biomass hybrid depends on the biomass fuel price and the amount of the load demand. Figures like 5.39 can be prepared and used as a decision map.

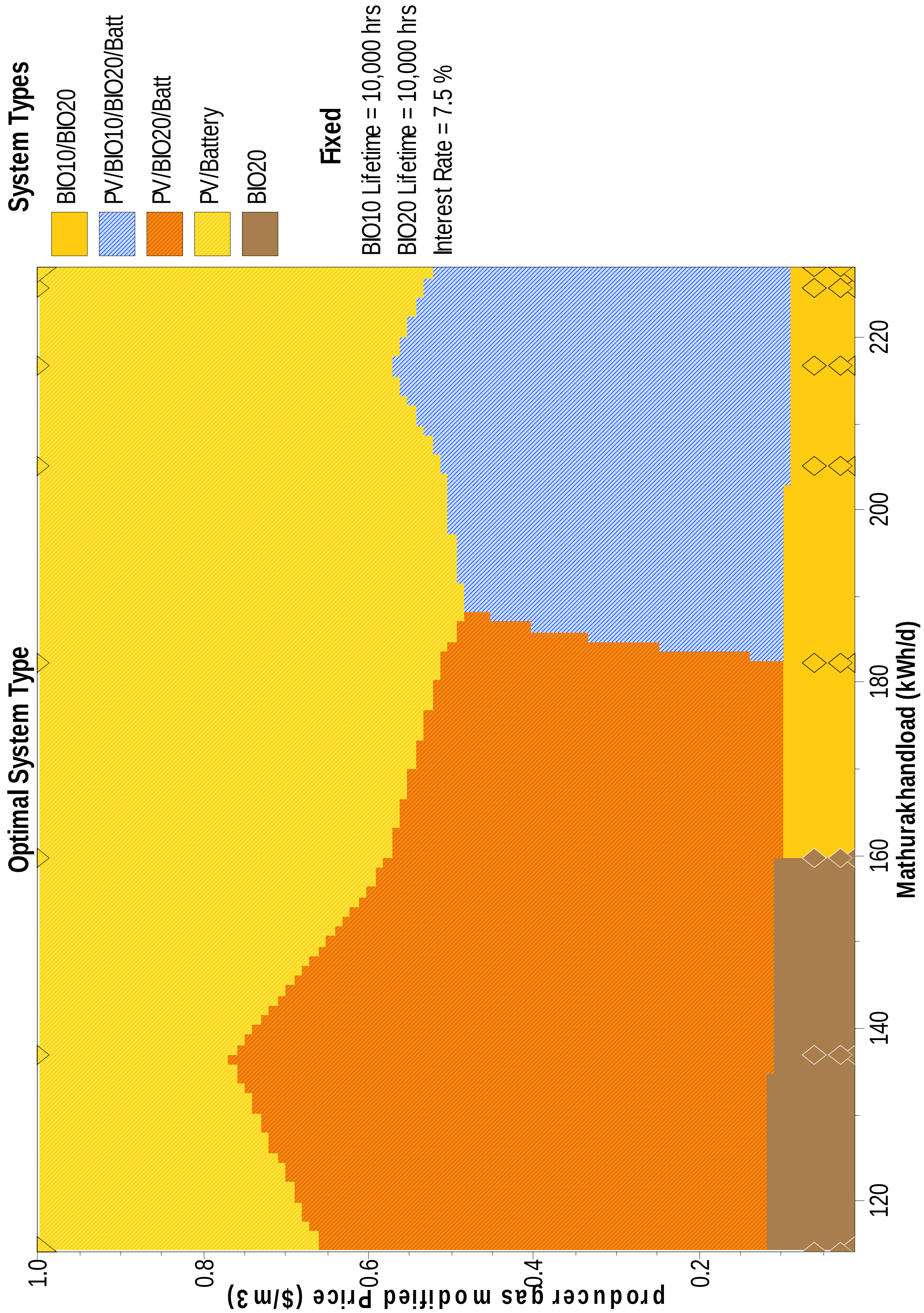


Fig 5.39: Optimum system configuration depends on biomass fuel price

(D) Effect of subsidy

Very often the RE power plant in Sundarbans region receive benefit of Government policy by which the initial capital costs for the equipments come from a mixture of various grants. In economic words, this is 100% capital subsidy. Therefore, when framing the appropriate tariff normally special care is taken not to retrieve money for the initial equipments from the consumers of the village power. Corresponding tariff figures reflect the subsidized cost of generation which is lower than the actual cost of generation. Actually in absolute terms the capital costs are borne by the Government or respective donor agency even though in this subsidised system consumers pay lower amount of money, Here the PV-biomass hybrid plant was re- calculated considering 100% capital subsidy. This can be compared with section 5.10.3.

In the section 5.10.3 we obtained the suggested configuration of 67 kWp PV with 420 batteries and 40 kW biomass gasifier incurring COE generation of 0.392 USD/kWh. The same configuration is again simulated considering zero capital costs.

Amla+Mathura load (kWh/d) 615

Double click on a system below for simulation results.

				PV (kW)	Bio40 (kW)	Batt.	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)
				67	40	420	60	$ 0	27,085	$ 276,122	0.126

Table 5.11: The effect of 100% capital subsidy

From the result it can be seen that the cost of energy generation came down to 0.126 USD/kWh which is only 32% of the actual cost.

If we recalculate the power plant performance, of section 5.11, with 100% capital subsidy then from actual cost of generation of 0.415 USD/kWh the value comes down to 0.129 USD/kWh. Performing ViPOR analysis considering 100% capital subsidy in generation as well as distribution equipments result in a cost of energy supply of 0.184 USD/kWh as against the actual value of 0.668 USD/kWh, which is only 27.5 % of the original figure.

It is evident from the above that the effect of subsidy is very major on the over all economics of the power system. In the context of small islands in developing countries the issue of subsidization on electrification project carries crucial role for success.

(E) Effect of load variation

For Mathurakhand village: A special exercise has been conducted where the village originally had 228 load points of identical 1kWh/day consumption (see section 5.10.1). The load points were synthetically reduced from 100% till 50%, corresponding to a total 114 kWh/day demand from 114 houses. At the end there are 11 sets of situations with 11 different values of load points which are also same as the total load sizes. Separate HOMER + ViPOR analysis has been made for each of these 11 situations considering PV-only option as given in section 5.10.1. Afterwards the cost outputs of the analyses were plotted against the corresponding load sizes. The graph is shown in the fig. 5.40. Another curve for LCOE is shown in fig. 5.41.

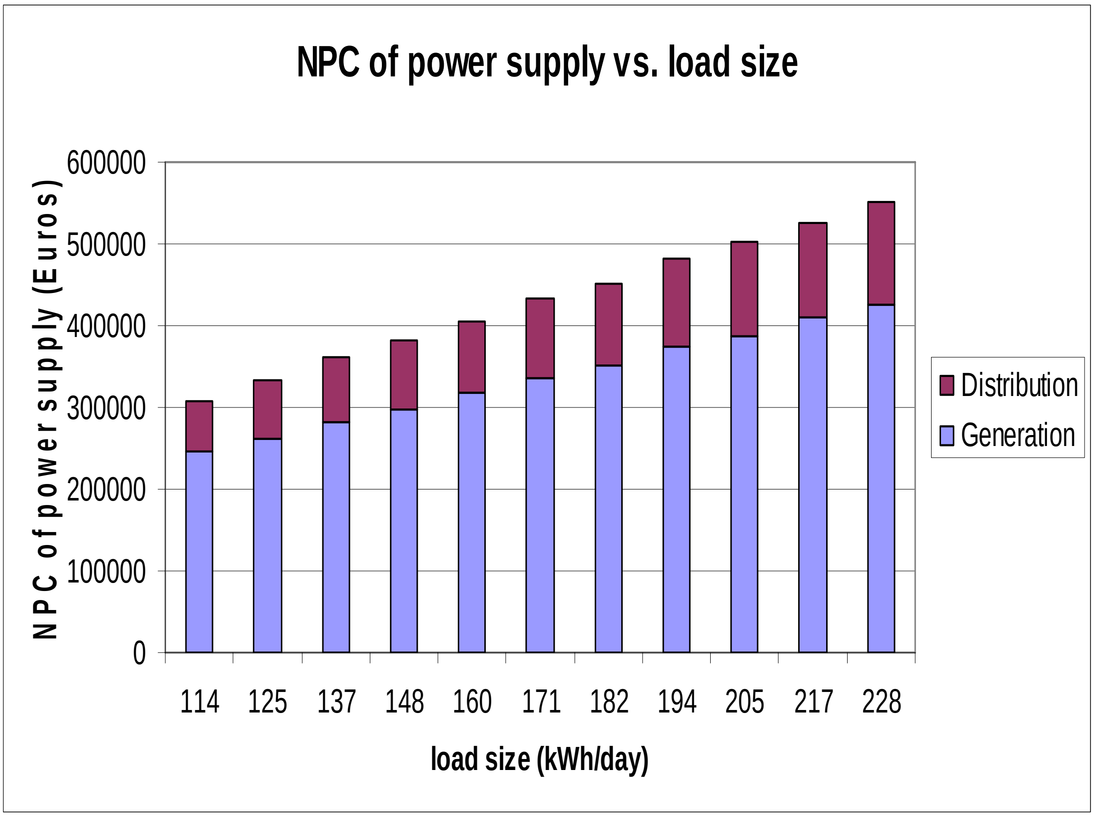


Fig. 5.40: The effect of load variation in PV based mini grid

It can be seen that the NPC vs. load curve is having a straight line relationship with a non-zero intercept and LCOE is decreasing with increase in the load size.

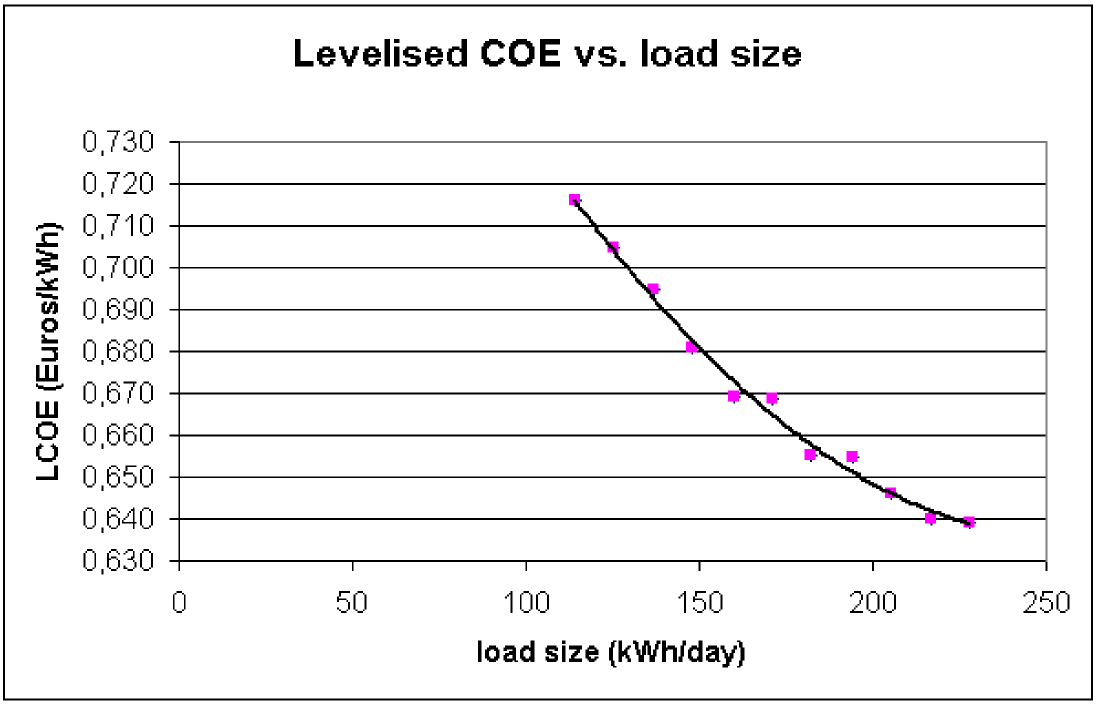


Fig. 5.41: The effect of changing load sizes on levelised cost of energy supply

(F) Effect of geographic dispersion of the load points for Mathurakhand

The effect of the terrain / land usage on the overall power distribution layout and cost has already been shown in section 5.10.4. Here a special analysis has been conducted to experience the effect of load density on the overall power system. By transforming the coordinates of actual load points in the village Mathurakhand, 6 different synthetic load densities have been created whereas the inter-distance among the load points have been changed in equal proportion. Keeping the cost of generation same as in PV-only case for 228 kWh/day load, separate ViPOR analyses have been conducted for each value of load density. It is obvious that in this case the difference in power system would result from difference in distribution system only as the total power consumption is constant for all load densities. The important results are shown in the figures as follows.

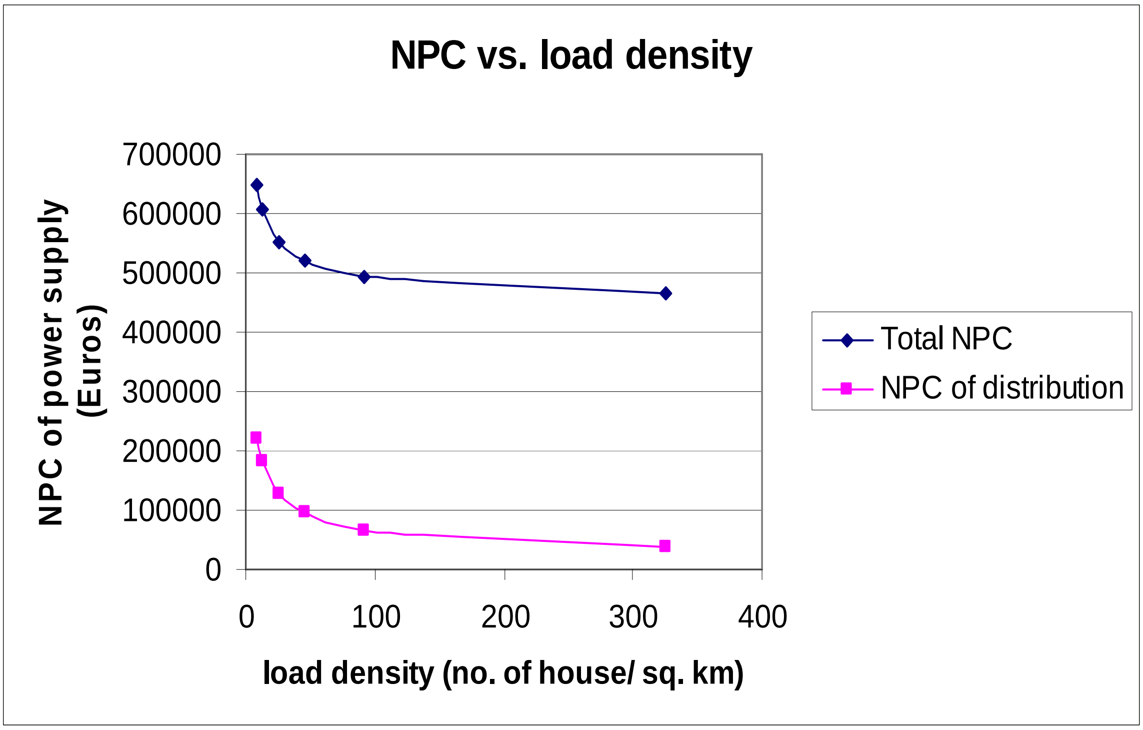


Fig 5.42: The effect of load density on NPC of power supply

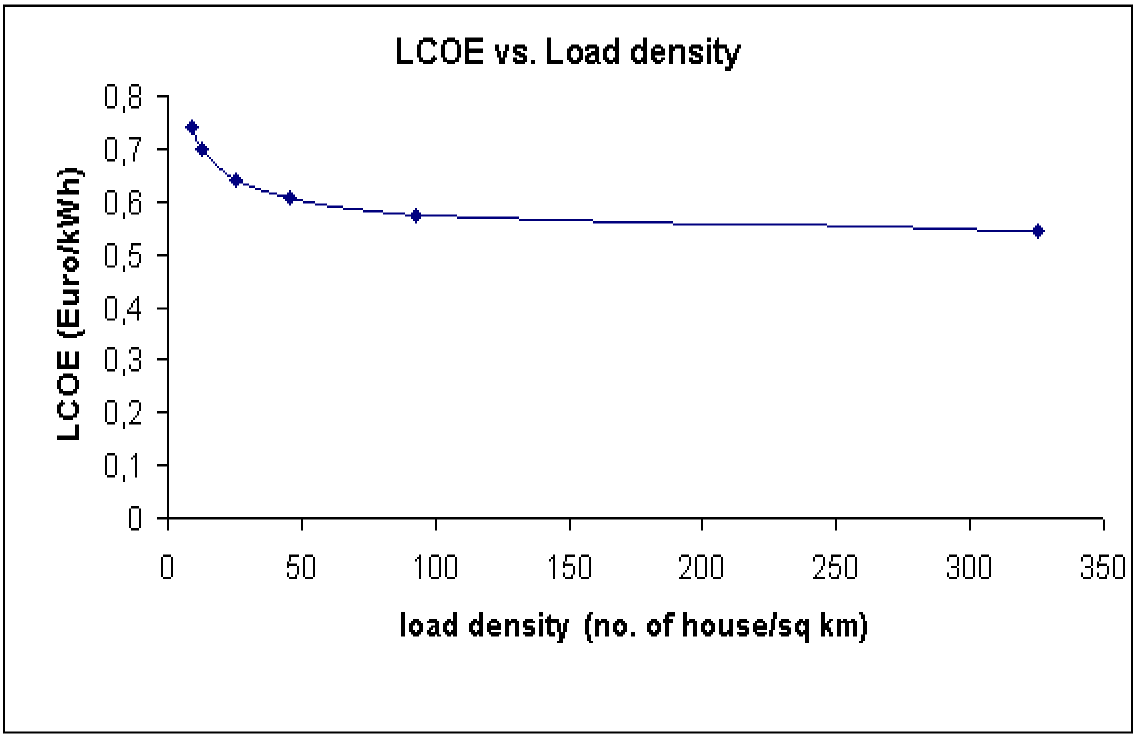


Fig. 5.43: The effect of load density on LCOE of power supply

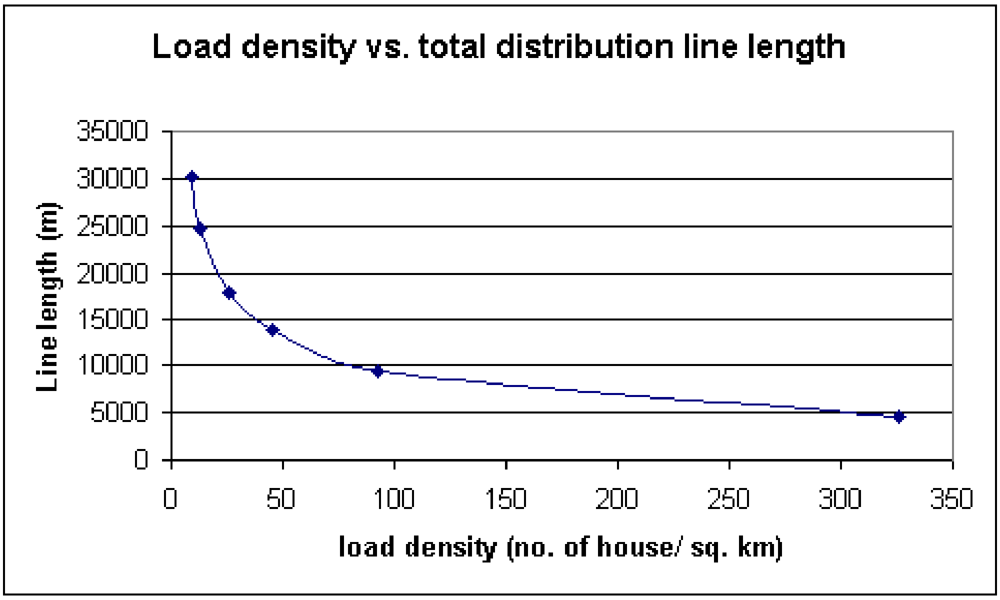


Fig. 5.44: The effect of load density on total distribution line length

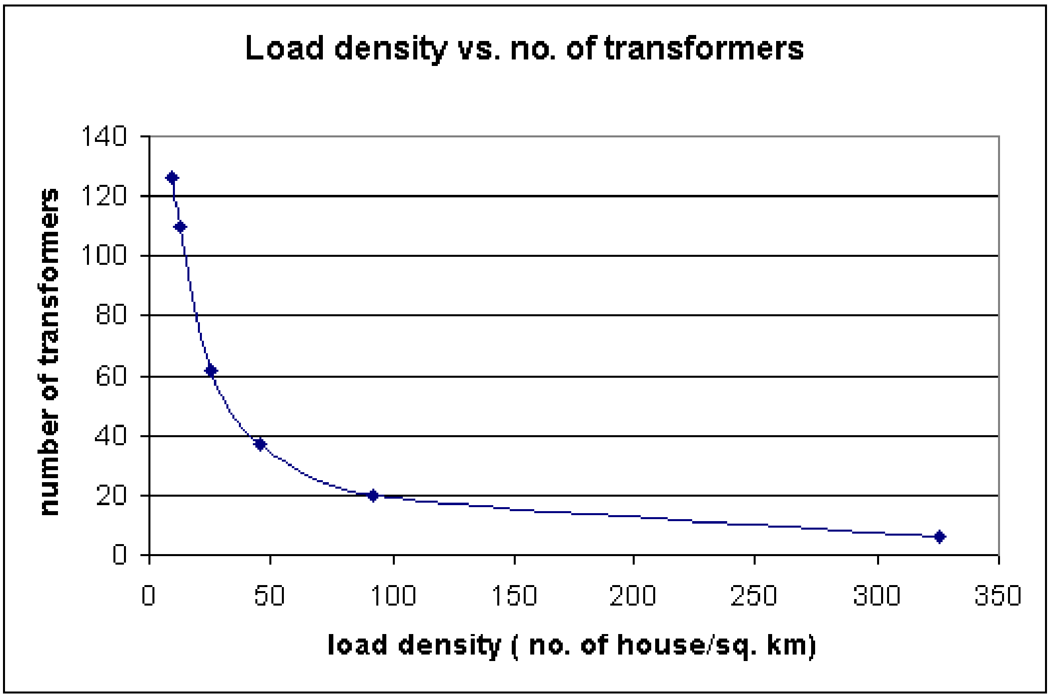


Fig. 5.45: The effect of load density on number of distribution transformers

In low load densities the overall cost per kW is found to be higher than that in higher load densities. Also as expected, the total overhead line length is decreasing with the increase in load density. Similarly the number of transformer is decreasing with increase in load density. However, because in higher load densities each transformer is reaching more number of houses, the loading on the transformer increases.

5.13 Conclusion of the case study

In this case study, an attempt has been made to follow the generic methodology developed in the last Chapter in order to arrive at optimal layout of a renewable energy based electrification system for the village Mathurakhand and Amlamethy in Bali island, India. Corresponding techno-economic features of the system were explored and analysed. Combination of remote sensing / GIS based analysis was integrated into renewable energy modelling tools in local scale. Solar photovoltaic and biomass energy technologies were considered for the analyses. The biomass gasification models were exclusively developed in HOMER for the case study. The weakness in HOMER-ViPOR integration technique has been removed in order to get more accurate results. The emphasis of this study was on the technical capability of solving an environmentally benign electrification task using remote sensing resources which are freely or cheaply available.

In a real life situation, developmental projects of this kind are highly dependent on the prevailing policy of the concerned authorities and organisation of finances for the scheme. In Sundarbans region, normally 100% of the capital cost comes from the combination of state and national government developmental schemes as discussed in the next chapter on tariff.

This study emphasizes the advantages of using high resolution satellite imagery for analysis. High spatial resolution imagery greatly facilitated the mapping of settlements and other features, thus reducing the costs of ground truth which was conducted in phase 2 of the case study. However, the limitations of the approach are exhibited in the inability to delineate settlements covered by trees and cloud cover over some portion of the region. **The effectiveness concerning time and cost is clearly evident due to the availability and operability of freely downloadable satellite imagery as well as Digital Elevation Models and energy modelling tools.**

The levelised cost of energy delivered to the rural people strongly depends on the spatial features of the target region and on the choice of the renewable energy system configuration besides various economic parameters. This validatory case study shows that it would be effective to apply the generic framework developed in the Chapter 4 to a specific island electrification project. **Thus before firming up finalized option for installing an actual island electrification project at a given location, it would be worthwhile to undertake similar effort.**

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Chapter 6

Tariff, Business Models and Impacts

The wide range of energy sources and carriers that provide energy services need to offer long-term security of supply, be affordable and have minimal impact on the environment. However, these three goals often compete. IPCC reports that "there are sufficient reserves of most types of energy resources to last at least several decades at current rates of use when using technologies with high energy-conversion efficient designs. How best to use these resources in an environmentally acceptable manner while providing for the needs of growing populations and developing economies is a great challenge" [1]. In this context the role of appropriate business models, management and organization, tariff system etc. are extremely important subjects for sustainable operation of any island electrification initiative. Equally interesting thing is to look into the changes that existing island electrification initiatives have really brought into the developing society with the help of renewable energy. This chapter addresses these critical themes.

6.1 Tariff

6.1.1 Basic principles of Tariff

For island electrification projects, covering all kinds of costs associated with the electric energy that is generated and delivered are critical for the success of the project. For this purpose, a properly designed tariff schedule defining what each consumer should pay for the service of electricity has to be established.

The traditional approach towards the fundamental principles of tariff determination for electricity in a conventional grid connected network is based on cost estimations associated with the power system. In general, the cost of generating and delivering electricity to the doorstep of the consumer can be roughly divided into the Fixed Costs (also known as standing charges), which do not vary with the operation of the system and Running Costs (also known as operating costs), which vary with the operation of the power system. Normally the size and cost of installations in a generating plant is determined by the maximum demand made by the different consumers [2]. Each consumer expects his maximum demand to be met at any time during the operation of the plant. Therefore, the generating equipments have to be held in readiness to meet every consumer's full requirement at all the time. This virtually amounts to allocating a certain portion of the generating plant and the associated distribution system to each consumer for his individual use. So, a consumer should pay the fixed charges on that portion of the plant that can be assumed to have been exclusively allocated to him plus the charges proportional to the energy units actually consumed by him. However, the actual situations in remote islands very often do not follow the ideal philosophy as described above. Government's support policies, financial revenue model on which the project is built up, ability and willingness to pay of the prospective consumers of electricity etc. are some of the important factors amongst many others in the complex process of estimating appropriate tariff for a particular electrification project in a small island. Also, the business objective of the utility concerned will have a profound influence on the tariff fixation. The sustainability of the projects is another concern on which the management and revenue model of the projects are generally designed and tariff becomes a vital part of the total management system.

6.1.2 Different types of tariff structures existing in India

Normally one utility distinguishes its customers as domestic, commercial or industrial users of electricity. The tariff rates differ for these different kinds of customers. In some cases and countries tariff is even based on time of usage.

Some of common tariff types in India are described below

- **Flat rate**

In this system the charge is made at a simple flat rate per unit of electricity. But the lighting loads and power loads are metered separately and charged at different rates. For a central grid connected power system, the lighting load has a poor load factor resulting in higher fixed costs per kWh generated. This is reflected in making the price per unit comparatively high. Whereas power load has a higher load factor resulting in lower cost per kWh generated and corresponding tariff rate is also lower.

- **Sliding Scale**

In this type of tariff structure, the fixed costs are collected by charging the first block of electricity units at a higher rate and then reducing the rates, usually in many steps, for units in excess of this quantity.

- **Two part tariff**

It consists of two parts (i) a fixed charge proportional to the maximum demand which is independent of the energy units consumed and (ii) a running charge proportional to the actual number of units used.

This type of tariff is expressed by a first degree equation like Euro [A x kW + B x kWh] where A is the charge per annum per kW of maximum demand and B is the price per kWh. The maximum demand is measured by a maximum demand indicator during a specific interval like a quarter of a year. Sometimes, the customer is penalized for his poor power factor by basing the fixed charges on kVA instead of per kW of maximum demand. Such kind of two part tariff is in common use at present for commercial and industrial consumers in countries like India.

6.1.3 Special case for not profit making projects

It should be clearly mentioned here that tariff structure for an existing power project depends on several factors in addition to the basic principles of tariff as described in the previous section. For example depending on the nature and business policy of the organization who is supplying the electricity, the motive can be set to generate profits. In that case the tariff will be structured in such a way that there would be certain percentage of return on each unit of electricity concerned as profit on top of the actual costs involved.

On the contrary, recognizing the socio-economic benefits from introducing renewable energy based electrification in a remote island in developing countries many authorities, world wide, rule out the commercial mode of earning profits. In that case, the basic philosophy becomes not for profit and the plants should essentially generate adequate revenue only to take care of operation and maintenance and replacement needs while the capital costs coverage come from different development grants and other arrangements. In the tariff structure, therefore, capital costs are not reflected. In India, for example, many remote rural electrification projects are designed in such fashion. In the remote islands of Sundarbans, total capital costs generally come from combination of central government's subsidy schemes for remote village electrification and state government's development grants.

The following two kinds of basic tariff philosophy are common in remote and small island electrification in developing countries.

- **Power based tariff –** Here the tariff rate is predetermined based on power level. For example a fixed amount of money is charged as tariff per month for two points of 11W light bulb and one point for small black and white television.

- **Energy based tariff –** In this system the tariff is calculated on the basis of actual units of electricity used by consumer.

In the following table the salient features of strengths and weaknesses of these two systems are highlighted [3].

Table 6.1: comparison between power and energy based tariff systems for island electrification

Tariff type	Strength	Weakness
Power based tariff	Simplicity for customers	Vulnerable to energy theft and abuse
	Costs regarding meter reading are avoided	Restricted electricity usage
	Possibility to avail the advantages of using load limiters	No check over uneconomical consumption of electricity by load limiters

	Load limiters prevent overloading of power system elements	Tampering the load limiters possible
Energy based tariff	Depends on actual energy consumption	Well organized service is required to maintain
	More scientific in terms of metered supply	Meter reading, billing and collection involve costs
	Possibility to use pre paid energy meters	Customers has to purchase the card periodically - reach and access of sales points often become an issue
	Prepaid metering implies avoidance of meter reading, billing, pending payment	Because of high cost and maintenance involvements prepaid meters are seldom used in poor regions

It should be mentioned here that perhaps the future trend of tariff type of a remote village will aim to follow the common practice in urban areas today, i.e. energy based tariff system.

6.1.4 Existing tariff rates in Sundarbans islands RE based electrification projects

From the year 1994 several island electrification projects have been undertaken by the local utility WBREDA, as described in the Chapter 1, 3 and 5. Several types of technologies have been deployed and also several kinds of management structures have been tried in Sundarbans. And the operation durations are also different in different projects so far. Therefore the tariff schemes are also not same for all projects. Many PV mini grids, however, follow similar tariff system. For obtaining a connection from the solar mini grid plants with average supply for 5 hours per day, a consumer is required to pay Rupees 500 for connection charges of 60 W connected load. The monthly tariff in form of lump sum energy service charge is Rupees 150 per month for 60W-connected load. Consumers are free to apply for more than one connection depending on their requirements and ability to pay. This 60 W connection is most common so far. People use 4 CFL light bulbs or 2 light bulbs and 1 fan or 1 bulb + 1 fan +1 television. In the wind – biomass-diesel hybrid mini grid plant in Sagar Island the similar flat tariff is operational as well. Whereas in Gosaba Island, with 500 kW biomass gasifier based power supply, which runs for 18 hours per day, a security deposit of Rupees 240 has to be made for providing the service connection and house wiring. There a three tier tariff structure has been set based on actual electricity consumption for consumers in Domestic, Commercial and Industrial categories. The tariff rates are Rupees 5 / kWh for domestic; Rupees 5.5 / kWh for commercial and Rupees 6 / kWh for industrial consumers.

6.1.5 Actual monthly tariff rates in the nearest mainland grid connected areas

West Bengal State Electricity Distribution Company Ltd., is the electric utility responsible for power distribution in the grid connected regions of the State West Bengal. Sundarbans islands areas are not covered by them where WBREDA is responsible o provide power through RE based local generation only. The tariff rates in this section are indicating the existing rates of the nearest grid connected areas [4]. 1 P (Paisa) = 1 Indian Rupee Cent.

A) For domestic consumers in rural areas

Unit (KWh)	Rate (P/KWh)
First 75	209
Next 105	232
Next 120	284
Next 600	325
Next 450	559
Above 1350	577

B) For domestic consumers in urban areas

Unit (KWh)	Rate (P/KWh)
First 75	214
Next 75	242
Next 150	289
Next 150	333
Next 450	352
Next 600	559
Above 1500	577

C) For commercial consumers in rural areas

Unit (KWh)	Rate (P/KWh)
First 180	287
Next 120	397
Next 150	422
Next 450	462
Next 450	547
Above 1350	547

D) For commercial consumers in urban areas

Unit (KWh)	Rate (P/KWh)
First 180	292
Next 120	402
Next 150	422
Next 450	462
Next 600	547
Above 1500	547

6.1.6 Existing tariff rates for shops in market places within the case study island in Sundarbans

There are three market areas in Mathurakhand and Amlamethy villages in Bali island: (1) Satyanarayanpur market with 40 shops (2) Raja bazaar with 25 shops and (3) Brihaspatibarer bazaar with 10 shops. Now, out of these three markets only Satyanarayanpur market has a facility of electricity service. One diesel generator of 5 kW capacity, owned and operated by a local private entrepreneur, is supplying all of the shops of this market. The existing tariff rate is Rupees 5 per connection per day for 2.5 hours daily service.

6.1.7 Proposed tariff for the case study developed within this study

The basis of estimating tariff is to calculate the cost of power supply. Generally it has been done in the form of levelized cost of energy supply over the total life span of a project. After that several factors are considered for addition in order to finalize the structure of tariff. Setting tariffs is a fairly complicated task that involves a lot of regulatory and policy issues. It greatly depends on what we want the tariff to cover e.g. 1) just the operating costs, 2) operating and replacement costs, 3) operating, replacement, and capital costs or in addition, some profit. There would be important tax and subsidy issues as well that are very country-specific. If the specific case includes capital costs then how much of a return on capital do we want to allow and how do we want to handle debt payments that will be paid off after a certain number of years. It also depends on the business motives of the energy supplier and associated business models as applicable to the specific case. Within a life span of an island electrification project, say at least 20 years, there will be escalation and changes in the costs of the individual components. Therefore the fundamental assumption is to fix the amount of cost values and exercise calculations accordingly. In reality the tariff figures, as obtained as described before, are being scrutinized in every fixed time interval e.g. five years. Depending on the situation prevailing at that time the tariff values are reset then. Also the tariff should be reasonable in terms of customers' paying capacity.

In this thesis only simplistic energy-based-tariff is exercised. Considering the socio-economic benefits of these power plants, earning profits on commercial basis has been ruled out in all of the existing projects in Sundarbans by WBREDA. Keeping the same philosophy as guiding principle the tariff has been calculated in this study. Essentially this means the project should generate adequate revenue to take care of operating and replacement needs. The actual levelized cost of electricity supply was estimated to be 0.668 USD/kWh (0.44 Euro/kWh) in chapter 5, section 5.11. It is obvious that in our case the tariff would arrive at a lower value as a result of excluding the capital costs from the consideration. The effect of subsidy on the power system has been described in chapter 5, section 5.12. Here the calculations are made considering no initial capital costs and the cost break ups are shown in the table 6.2. The total electricity service per year equals to 244577 kWh. Therefore, the cost of energy supply per unit of electricity comes about 0.184 USD/kWh (0.12 Euro/kWh). Now, this figure of cost of energy can be treated as a basis for setting up the tariff in the case study area. It should be mentioned here that the calculations in Chapter 5 were done considering a 'real' rate of interest of 7.5%. In reality the cost situation will be affected by inflation. Thus, we can escalate the cost of energy by an amount accounting for inflation. For example, a nominal rate of interest of 13% with 4.5 % inflation give the ‘real’ rate of interest of 7.5%.

Table 6.2: cost break ups for 100% capital subsidy case

	Generation	Distribution	Total
ITEM	**COST (USD)**	**COST (USD)**	**COST (USD)**
annualized capital	0	0	0
annualized replacement	25911	0	25911
annualized O&M	4529	13466	17995
annualized fuel	6785	0	6785
annualized salvage	-5612	0	-5612
total annualized cost	**31613**	**13466**	**45079**

If we consider the present rate of inflation of 9.5% in India, an escalation of 5% over the 0.184 USD / kWh results in a slightly higher value of 0.193 USD/kWh (0.13Euro/kWh) which can be considered as a simplistic tariff rate for the case study.

6.2 Business models

For the successful performance of island electrification projects local institutional arrangements, particularly ownership and management, become very crucial. Very often such a project is of small capacity which implies a probability where only the local promoters are involved into the core of the project with their limited resources and capabilities.

The World Bank [5] has categorized the business models for a mini grid type rural electrification project into following four general classes:

1. Utility model

2. Community based organization model

3. Private sector model

4. Hybrid model

According to the World Bank, utility models are the most common for rural electrification in developing countries and many of these projects are based on diesel generators or hydro power. The main advantage is the technical know how and financial strength that utility companies have. Also, dealing with subsidy mechanisms come normally easier within or between public companies. The principal disadvantage of this model comes from lack of priority for a typical utility as it involves low revenue generation situation. Sometimes utilities in developing countries become inefficient and driven by political agendas. Tunisia, Mexico and Thailand have some well-run projects in this category.

Community based models are the most common for renewable energy based mini- grid type electrification projects. This model has stronger interests, ownership and presence in managing the system. However, there is a risk of weakness coming from lack of technical as well as managerial skills Institutional support and capacity building is a crucial requirement of the community cooperatives model. Rural electric cooperative is a variation of this model which is a consumer owned system that distributes the electricity to its members. The cooperative can purchase and resell grid-based electricity, or it can operate an independent mini-grid system with its own generating source. This business model has been successful for rural electrification in a number of countries, such as in Bangladesh, Costa Rica, the Philippines, and the US.

Under private sector model, large private (or public-private) utilities or small rural energy service companies are responsible for developing, owning and operating mini-grid systems. The principle advantage of private sector model is that they generally have a local interest in providing electric power services. Compared to public utilities, they can also eliminate some of the political interference. However, the private sector cannot be expected to serve poor rural populations without some form of public policy supports. A limitation of private sector model is that local private energy entrepreneurs usually are small, have limited technical skills, and lack financial resources. To date, according to the World Bank, most funding for local rural energy entrepreneurs has come from either government or multilateral sources. In a few South American countries, particularly Chile and Argentina, private rural energy service companies have successfully operated.

A combination of the above three business models could become an effective local institutional arrangement in form of a hybrid model for renewable energy mini-grids. For example, a utility or a private company can own and develop a renewable energy mini-grid system, while a community-based organization can manage the day-to-day operation of the system, and the utility or the private company can provide technical back-up and management advice. One of the barriers to the development of commercially-viable projects for village or rural community applications is that village leaders do not possess the technical skills and financial resources to develop these projects on their own. One solution to this problem is to provide organizational, technical and financial support to the local leaders to promote the project development process. The other approach is to provide incentives to a private rural energy service company (RESCO) that would sell systems to villages using a co-investment approach. The RESCO invests as a minority owner in the project, and it helps the village owner/entity obtain financing to leverage their investment funds [5].

In the figure 6.1 a matrix, as developed by the World Bank on business models for rural electrification, is shown.

It should be mentioned here that there are some interesting business models throughout the world. The detailed discussions on the nature of these well known models are beyond the scope of this research.

Here the names of five selected eminent business initiatives are listed for reference

- **Grameen Shakti**, Bangladesh (also famous for micro finance concept and Grameen Bank) : www.gshakti.org
- **SELCO**, India : www.selco-india.com
- **SUNLABOB**, Lao PDR : www.sunlabob.com
- **Barefoot Power**, Australia : http://barefootpower.com

- **Bushlight** programme of Centre of Appropriate Technology, Australia : www.bushlight.org.au

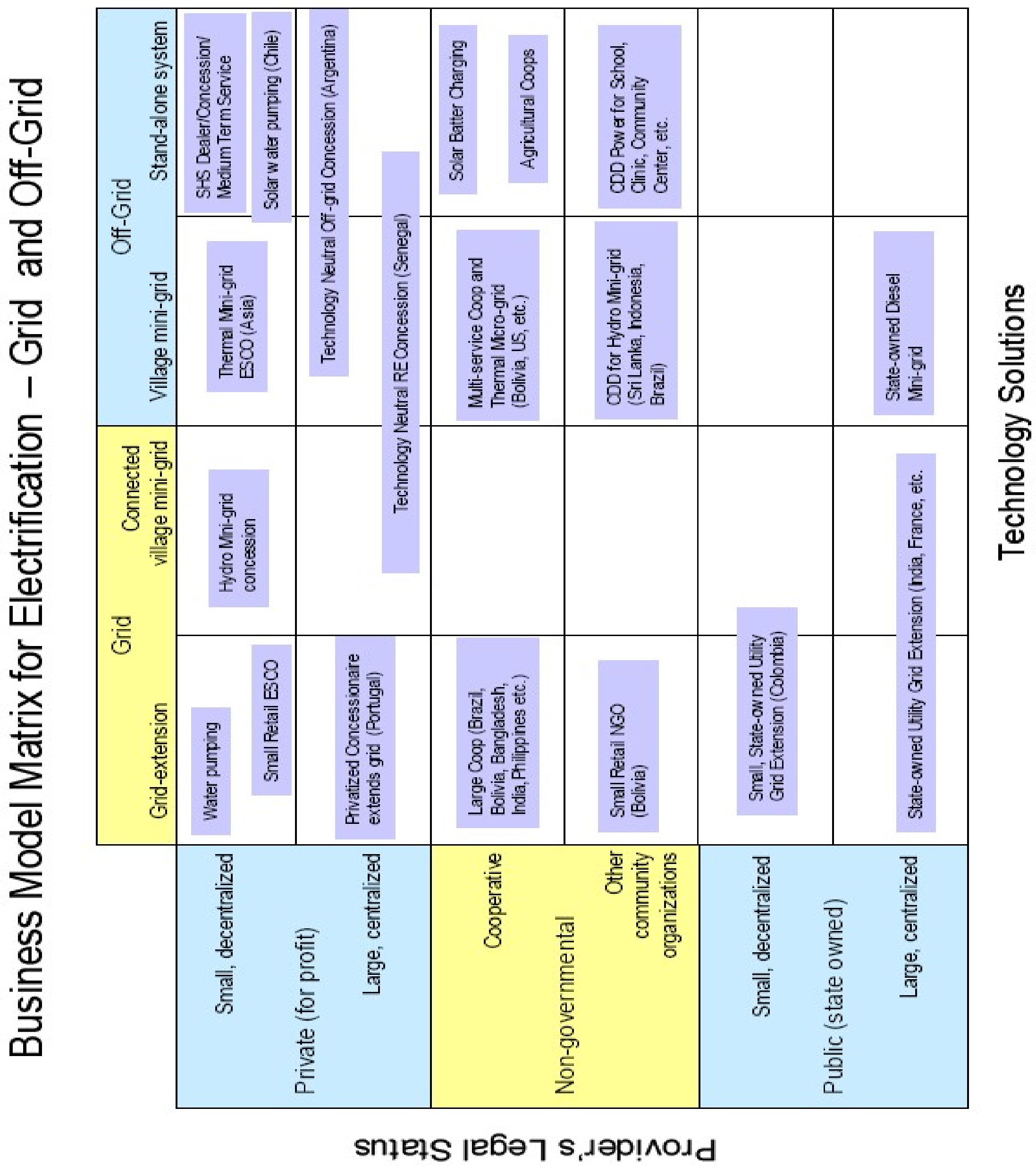
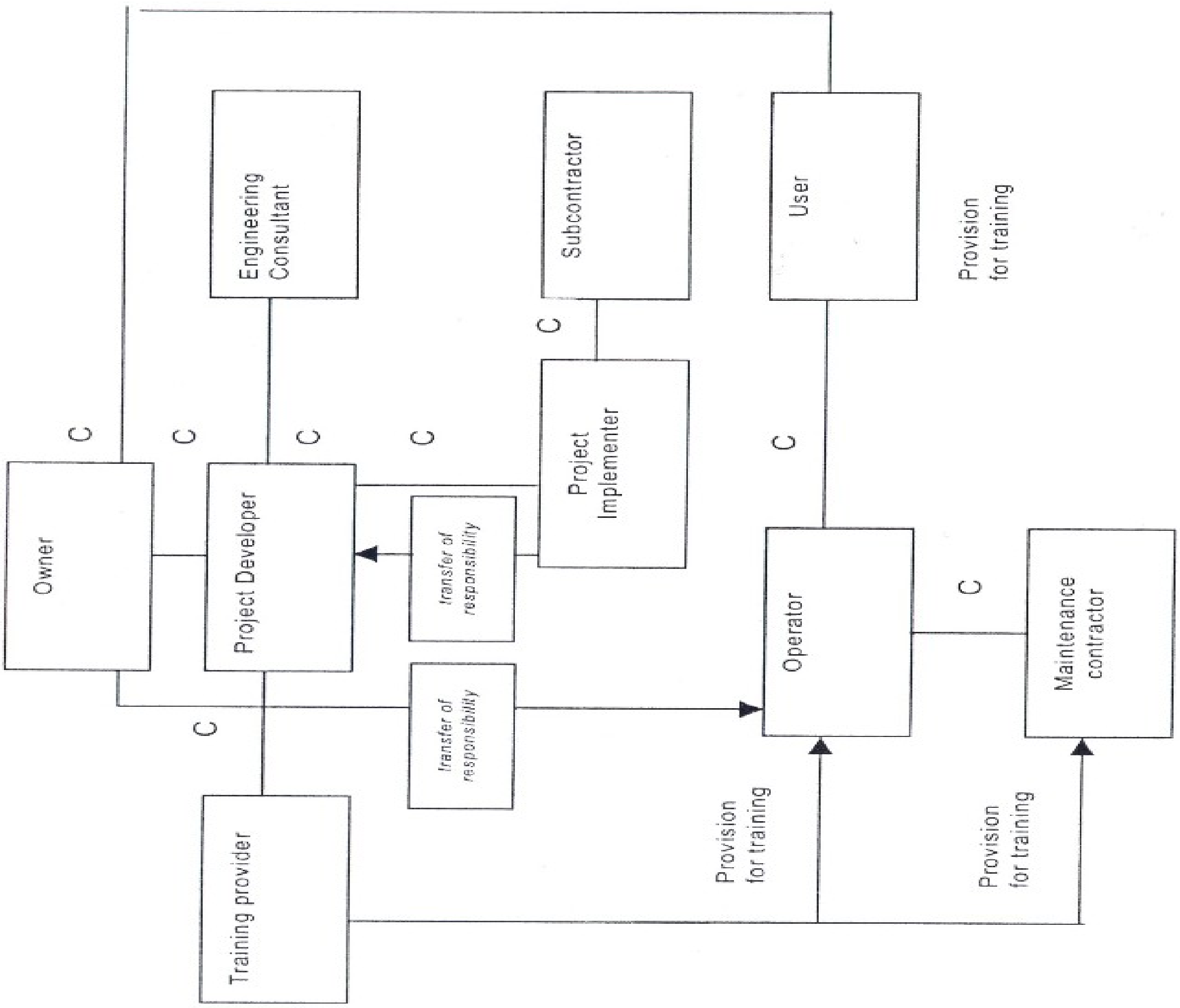


Fig 6.1: The matrix of rural electrification business models (source: [5])

Part 3 of the draft IEC recommendations (IEC 62257-3) for small renewable energy and hybrid systems for rural electrification is dedicated to a theme of "project development and management" [6]. This document is very relevant to the subject of operating and maintaining a rural electrification project successfully.



Note: “C” represents a potential contractual arrangement between two connecting parties

Fig 6.2: Contractual relationships among project participants (source [6])

The document provides information on the responsibilities in the implementation of rural power systems. It discusses on contractual relationships that should be built among the different participants of a project. Figure 6.2 depicts such a contractual relationship pattern. This document also covers other important subjects like relevant tests to be conducted, quality assurance issues and recycling, environment protection etc.

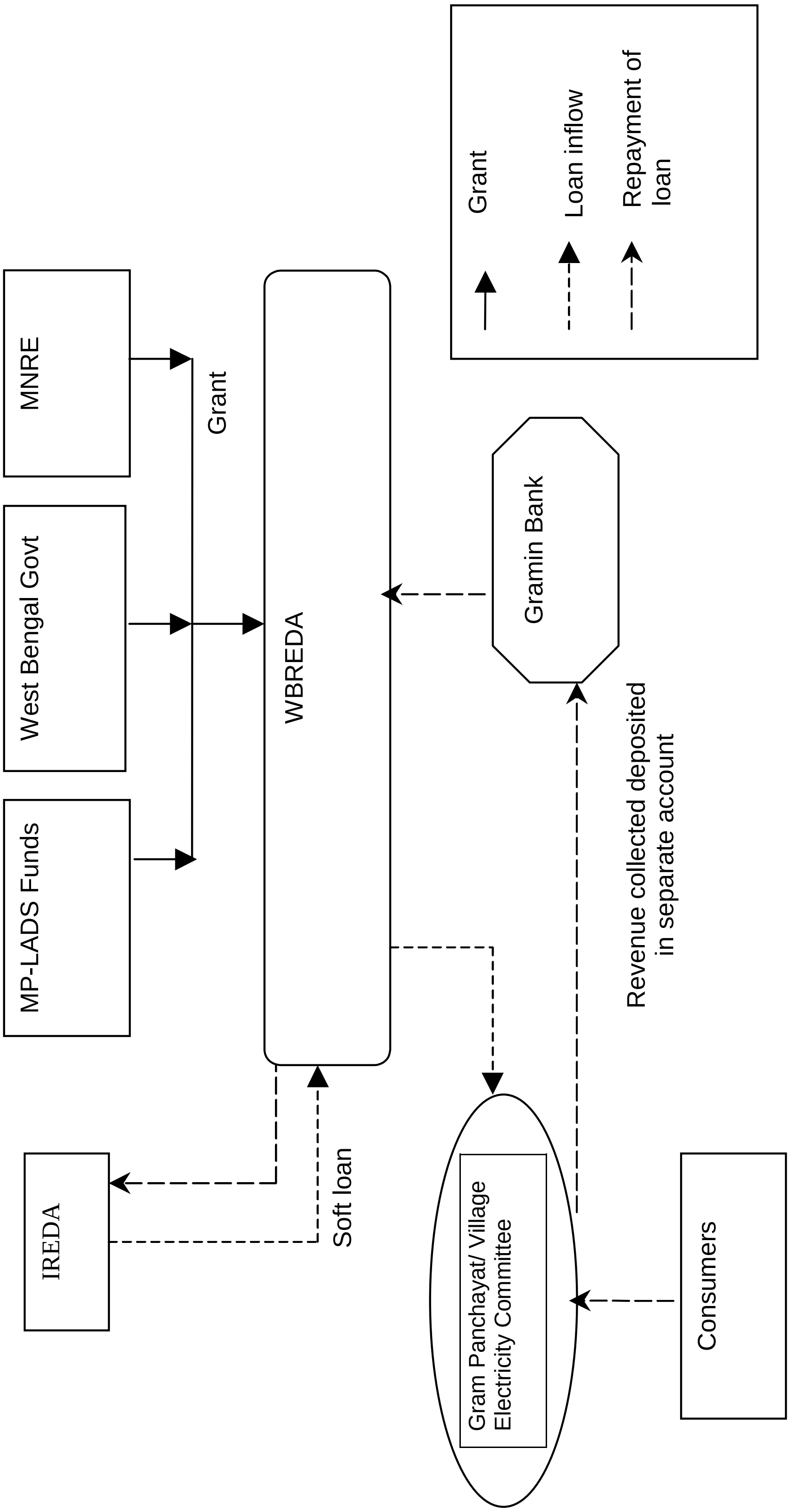


Fig 6.3: Typical financial structure of Sundarbans mini-grid projects (source [7])

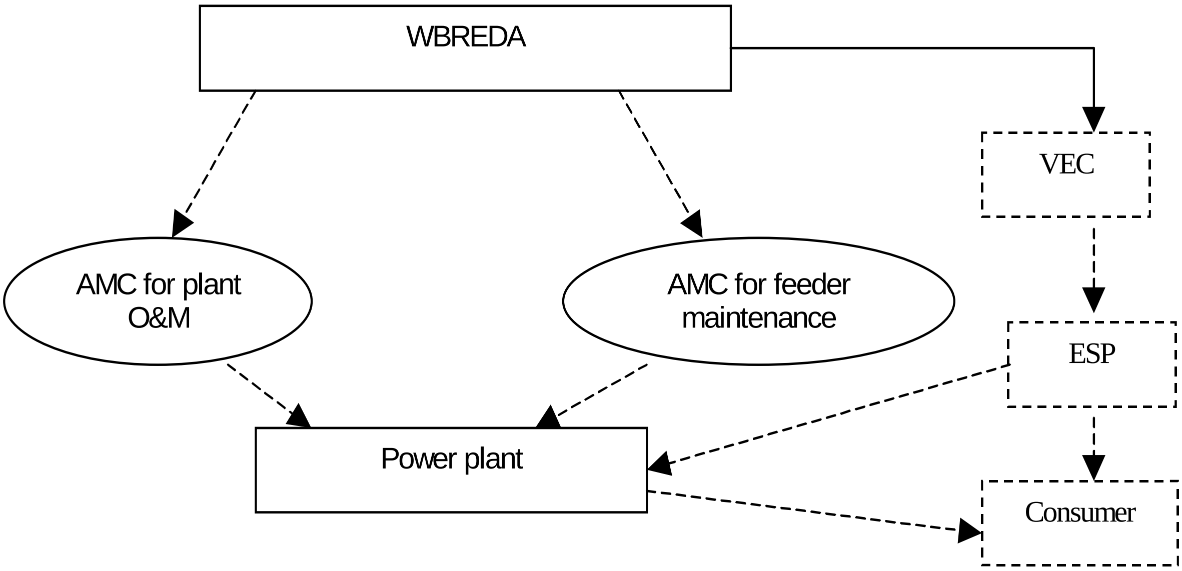


Fig 6.4: Typical institutional framework in Sundarbans mini-grid projects (source [7])

The guiding principle of the Sundarbans model is to implement a judicious mix of subsidy for initial capital costs from a combination of government grants and soft loans; community contribution in form of land for the project and initial connection charges and consumption charges through the fee for electricity service. The typical financial structure and institutional model are shown in the figures 6.3 and 6.4 respectively. In case when there is a monetary contribution from loans, WBREDA takes them and acts as a rural ESCO albeit not in strictly commercial terms but in that it facilitates the electrification process by owning all of the assets associated with the power plants and guaranteeing a reliable supply of electricity to the consumers. Individual consumers own the internal wiring and appliances and pay for the services they use.

The installation of the systems are facilitated by WBREDA and separate Annual Maintenance Contracts (AMC's) are awarded by WBREDA for

1. Plant operations and management and

2. Distribution Line maintenance

The contractor for plant maintenance has to provide trained and qualified operator (s) for day-to-day operation and maintenance works. The operators are to maintain daily log sheets of the power plants. The line maintenance contract can be given to a local contractor, which gives boost to local entrepreneur. A Village Electricity Cooperative (VEC) is constituted in consultation with WBREDA. It consists of all consumers as its members. An elected representative of the consumers becomes the chairman of the Society. A core group comprising of the chairperson, 5 elected members from the consumers and a WBREDA representative are responsible for administration and monitoring of the VEC. VEC is also responsible for grievance redressal and tariff determination. Tariff is worked out by the VEC in consultation with WBREDA on the basis of the calculated costs as well as on the basis of what members of the cooperative are willing to pay. VEC gives "Electricity Service Provider' (ESP) contracts for billing, metering and revenue collection services. The service provider forms a team of up to 1-2 people chosen by the core group of VEC in consultation with WBREDA. The ESP team is trained on key aspects pertaining to its effective functioning. The income of ESP is directly linked to the revenue collection efficiency in their area. VEC monitors working of ESP, which in turn is responsible for collection of energy service charge and disconnection of any defaulters. In case of non-repayment of bill by a consumer for more than 2 months, the service is disconnected. For reconnection a written application, payment of outstanding energy service charges and a reconnection fee have to be made which acts as disincentive for non-payment. Revenue collected from the sale of electricity is deposited in a separate account for transactions with WBREDA and provides for the costs of the operation and maintenance of the plants. The ESP members, typically selected for a period of two years, are under close scrutiny of VEC. By accessing finance through various developmental funds for setting up the village level utility and ensuring its O&M from the sale of electricity this business model thus ensures clean electricity services with acceptable tariffs to the rural consumer.

6.3 Impacts of island electrification on the society of Sundarbans

6.3.1 Introduction

Energy services are fundamental to achieving sustainable development. The main goal of all energy transformations is to provide energy services that improve quality of life and productivity. Meeting the essential energy needs economically and in sustainable manner requires a judiciously balanced energy portfolio suitable for the economic, social and resource conditions of individual islands. IEC says, “Rural electrification is one of the predominant policy actions designed to increase the well-being of rural population together with improved healthcare, education, personal advancement and economical development” [6]. IPCC observes that in many developing countries, provision of adequate, affordable and reliable energy services has been insufficient to reduce poverty and improve standards of living [1]. Low electrification rates correlate with slow socio-economic development. IPCC reports, “Analysis from 125 countries indicated that well-being and level of development correlate with the degree of modern energy services consumed per capita in each country” [1]. Lack of adequate energy access frustrates the aspirations of many developing countries. Adopted by the international community in 2000, the United Nations’ **Millennium Development Goals (MDGs)** outline specific development objectives to be achieved by 2015. Although energy is not explicitly mentioned in MDGs, there is growing recognition that energy services play very crucial role in development efforts and in the living conditions world wide [8]. Achieving this target implies a need for increased access to electricity for millions of people in developing countries mainly in South Asia and sub-Saharan Africa. As mentioned in Chapter 2, providing reliable access to electricity can and should have positive impacts on human development, by providing preconditions for the development of new economic and social activities. There is belief that electrification should target income generation and that it is important to focus on improving productive uses of energy as a way of contributing to income generation by providing services and not as an end in themselves [1]. REN 21 concludes that in many circumstances, renewable energy sources have an important role to play in an energy portfolio that supports the achievement of the MDGs [8]. On the other hand, ‘social acceptance’ is a prerequisite for the adoption and introduction of new technologies- in particular new public infrastructures. The importance and nature of social acceptance with respect to renewable energy technologies have been described in several publications including [9], [10], [11], [12] and [13].

In the light of the above, an effort has been made in this section to investigate the impacts of the islands electrification initiatives in Sundarbans on the local human dimensions.

6.3.2 Impacts in Sundarbans

One of world's most unique ecosystems is represented by the Sundarbans islands of India. There human settlements are distributed amongst several deltaic islands within an island cluster in geographically non-uniform manner. The rest of the islands contain the largest mangrove forest of the world, protected by the government and recognized by the United Nations as described in Chapter 5. Therefore people are living there in very proximity of the protected flora and fauna in every sense. This calls for a stringent mechanism where the development of the villages can take place without disturbing the sensitive eco-system. The entire region was lacking access to electricity before. As described in chapter 3 and chapter 5 that since the year1994 government of India has built several electrification projects which are based on renewable energy technologies. However, many villages are still without electricity where government is undertaking various electrification projects one by one. The impacts of remote rural electrification in this area become vital in the efforts through adequate recognition and accounting of human dimensions. In the section 6.2 of this chapter, and particularly in figures 6.3 and 6.4, the business model and institutional structure of the electrification initiatives are described. It can be seen from these that participation of the local people from the planning process itself to all spheres is essential part of it. **This ability to participate, ability to be heard, access to information in all stages of the management are the causes of success there**. **The inspiration and compassion of a caring community, involved in planning, operating and managing, strive automatically for sustainability and development.**

In general, the consumers there are happy to receive the benefits of electricity service. A large number of fresh applications for new connections, from non electrified section of population, have been submitted to the local electrification authority WBREDA. **This high scale willingness for receiving renewable energy based electricity carries immense social dimension and is very important evidence in favor of the acceptance level** in the island society which is built since 1994 through creation of successive electrification projects.

The emergence of electricity has led to significant changes in the society including economic growth, education, resource conservation, health and social status amongst many others. Drinking water and health care provisions are enhanced. The use of renewable energy is also a major contributor towards preservation of the enormous biodiversity of the largest mangrove ecosystem inhabited by endangered species of flora and fauna. Institutional linkages with government have been strengthened and a pragmatic approach to the plights of the rural population has been adopted. Social sensitization towards the environment has been proven achievable. Table 6.3 shows a summary of how the RE projects are helping to achieve MDGs there.

Kemmler et al. [14] have discussed in details about the energy–based sustainability indicators. They have ultimately used the following indicators for India - Energy Resource Conservation; Economic Activity and Efficiency; Climate Change; Regional, local, Indoor Air Pollution and Poverty and Equity. In the following part some of the important facts from electrified regions of Sundarbans islands are mentioned.

1. **Reduced usage of fossil fuels**:

    - Reduction in purchase of kerosene for lighting is to the extent of 60% in households and 100% in shops.
    - Each 100 kWp mini- grid has potential of saving 180 tonnes of CO_2 per year.
    - In Sagar Island, 5 diesel generators have been removed with associated fuel savings of 1800 litres diesel oil per year.

- Kolkata Port Trust is consuming electricity from the wind-biomass-diesel- hybrid plant of Sagar Island and recorded a reduction of 2600 litres of diesel per month.
- Gosaba biomass power plant had generated 6.5 million kWh electricity during 1997-2006 which is equivalent to saving 0.85 million litres of diesel with associated cost of INR 20 million.

2. **Economic perspective**:

- Growth in commercial activities in terms of goods and services.
- New kinds of facilities have been introduced like electronic shops, medicine shops, ice cream shops, photo copy service, video halls (earning INR 150 on average per video show), small fabrication units etc.
- Community based cold storages are being introduced which will provide service to fish vendors charging them on hourly basis.
- Introduction of several tutorial centres for school children running at evening. Tutor pays INR 130 per month but earns four times on average
- Cultivation of some specific agricultural products like betel are now being done in the evening.
- A few economic activities like sewing, weaving etc. are now done with the help of electricity.
- Because of the electricity supply in the evening the business hours in market places have extended with more income generation potential associated. Particularly jewelry making, watch repair, vehicle repair etc. have harvested the benefits of working after daylight.

3. **Urbanization**:

    - No significant changes in the domestic sector in the number of inhabitants but growth in commercial shops.
    - People enjoying TV and radio which has tremendous values in awareness, knowledge, access to information, connectivity and recreation.
    - In some of the locations, drinking water pumping system has been coupled with the power plant.
    - Now some islands are enjoying the power of communication with rural telephones. In some islands mobile telephone facilities have already been introduced.
    - Study duration for students in Sagar Island has been increased by 2.5 hours daily due to electrical lighting.
    - There are a few computer training centers started recently in Sagar Island.

4. **Health**:

    - Not only preservation of medicines in refrigerated enclosures offered by various drug stores but also treatment facilities have been expanded. Hospital in Gosaba now performs surgeries.
    - Vaccines like pulse polio etc. are now being kept in local medical centres.
    - The rate of death from snake bites has been significantly reduced with the help of anti venom kept in refrigeration and also because of the adequate street and home lighting facilities.
    - Avoidance of kerosene lamps brought better indoor air quality and illumination level substituting fire and smoke hazards.

As early as in the year 2000 Chakrabarti et al. [15] had conducted a detailed research in selected regions within Sagar island. They had concluded that there had been noticeable improvements and significant impact on education, trade and commerce, entertainment, health etc. as a result of supply of power from PV power plants. Productivity level of some agricultural activities as well as women’s participation in different economic activities (at night) other than household work had shown definite signs of betterment. They had worked on the following benefits for households from PV mini-grid plants:

1. Availability of longer period of study
2. Saving of time for cooking
3. Movement at night
4. Entertainment
5. Time for households work at night
6. Physical comfort
7. Doing agricultural work at night
8. Availability of longer period for trade and business
9. Increase in income for extended hours of work

To sum up the situation in Sundarbans it can be said that during over last 15 years WBREDA has taken several initiatives to electrify the region. The existing consumers are enjoying the benefits of electricity. Very large sections of people from yet non-electrified areas want to have new connections. WBREDA has many new projects in the pipeline. This has become like a small revolution in favour of renewable energy based electrification in islands. Electrification in Sundarbans islands has been exemplified as a strong mechanism of involving people in contributing their share towards the challenge of global change.

Table 6.3: MDGs addressed by the island electrification in Sundarbans

MDG 1: Cutting extreme poverty and hunger
✓ Growth in commerce, shops, medical clinics, cold storages, fabrication units ✓ Reduction of money spent on lighting energy services by kerosene - 60% in households, 100% in shops ✓ Generating light to permit income generation beyond daylight ✓ Activities like sewing, weaving are done now with electricity ✓ Introduction of new business like study tutoring, video halls
MDG 2: Universal primary education
✓ Providing light for studying beyond daylight ✓ Introduction of TV, radio, rural telephones, mobile phones, computer education centre which give access to educational opportunities ✓ Provision of electricity in schools
MDG 3: Gender equality and women's empowerment
✓ Freeing women's time for survival activities, allowing opportunities for income generation ✓ Reducing exposure to indoor air pollution and improving health ✓ Street lights for safety
MDG 4,5,6: Health
✓ Providing access to better medical facilities ✓ Allowing medicine refrigeration and equipment sterilization ✓ Reduction in death rates from snake bites ✓ Reducing exposure to indoor air pollution and improving health ✓ Providing access to health education media
MDG 7: Environmental sustainability
✓ Reducing GHG emissions ✓ Helping energy security issues ✓ Helping against fossil fuel depletion issues ✓ Providing access to safe drinking water ✓ Restoring eco-system integrity

Conclusive remarks: In order to make an island electrification project successful and sustainable, the role of appropriate business model, management and organisation and effective tariff structure are crucial. In Sundarbans Island cluster projects the local people were involved into several activities. The positive impacts of the electrification initiatives are profound there. This chapter also explains the tariff system and buiseness structure of the initiatives there.

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Conclusions and Outlook

1. About the research

This doctoral study titled "**Optimum utilization of renewable energy for electrification of small islands in developing countries**" has been conducted with a particular focus on techno-economic aspects. Introduction of this thesis details out the rationale and the structure of the works. The specific key objectives of the research are repeated here

- To investigate the state of the art in several aspects of technology, tools and practices for small island electrification
- To document good practice cases
- To develop a generic methodology for small island electrification with RETs
- To test and validate the developed methodology by conducting a case study
- To investigate the effect of existing RE based electrification projects on the island life

2. Conclusions

<u>Electricity from Renewable Energy in Small Islands of Developing Countries</u>

The 1st chapter sets the scene through an overview of the general issues of island electrification worldwide and deals with overall experiences and statistics of RE based island electrification initiatives. It shows that **small islands possess special characters which are attractive for deployment of renewable energy**. **Most of the mature types of renewable energy based technologies in the small islands have been tried globally**, including those in developing countries. The progress made by islands in developing countries is often found inefficient and inappropriate. Lack of adequate institutional structure and organisation of service delivery often create problem in sustaining the successful project life. The chapter lists selected successful island electrification projects.

Technology for Island Electrification

The second chapter discusses selected technical issues for island electrification which includes power quality requirements, power supply systems and autonomous hybrid energy configurations and conducts survey on useful software tools for designing island electrification projects. A review has been made for the application of remote sensing (RS) and geographic information systems (GIS) suitable for small island electrification. Small islands in developing countries sometimes represent the similar energy situation as in remote rural villages in the main land. **The challenge there is to supply rural areas with energy services that not only are good for the environment, but also provide social and economic benefits**. Satisfying basic human needs with modern energy carriers requires relatively small amounts of energy. Conventional approaches to extending energy infrastructure are very often economically inefficient in such locations. Such a small island would typically have single phase resistive type domestic loads supplied by overhead radial distribution system, if at all electrified. **Renewable energy based hybrid configurations with storage unit often become economically attractive than single resource autonomous systems.** Power generation coupled at DC or AC or mixed DC/AC bus system is possible while each type has specific strengths and weaknesses. Several software tools exist for RE generation design. HOMER and ViPOR, these two software tools in combination can be used for designing and optimising a rudimentary power system. The design philosophy of a rural distribution system is dominated by voltage drop considerations. In low load density situation, as typical in such islands, American type layout involves low capital cost. Usage of RS and GIS are commonly practised both for general RE applications as well as for rural electrification projects. However, village scale autonomous electrification plan using RS/GIS has not been reported so far.

Distributed generation and microgrids for small island electrification in developing countries

The 3rd chapter reviews the concept of distributed generation (DG) and microgrids as emerging technologies which are pertinent for electrification for small islands in developing countries. It also analyses the features of one pilot field project. **Need for access to adequate form of electricity is the main driving force favouring DG there**. Sundarbans cluster in India represents an example of large scale deployment of DG in developing country islands. The success of the renewable energy programme, which was initiated in the islands in the early 1990s, has been so remarkable that the **Sundarbans may be considered a rather unique hub of stand-alone renewable energy systems**. One of the key benefits of grid-connected DG is the increase in service quality, reliability and security. Microgrids can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. There exist several technical challenges to achieve ideal island power systems suitable for remote locations. However, even today microgrids can be realized with commercially available components. **A real mini-grid system in Kythnos island in Greece has been described**. This 10 kWp PV plant is distributed in five array locations. Three AC coupled battery inverters of 4.5 kVA each are forming the mini-grid with the help of a 53 kWh battery bank and one back up diesel generator. **The measured data analysis has shown that the plant is performing satisfactorily with regard to maintaining the voltage and frequency of the power supply.**

Methodology for small island electrification with renewable energy

The basic functional characteristics of island electrification process as a system are shown in this chapter. **The key factors influencing design of an electrification project have been identified**. Utilities should aim to provide the highest level of service possible within economic constraints of the consumer's willingness to pay. **The intermittent nature of solar and wind energy resources demands special attention in the design process**. Efforts were made to develop a methodology for electrification plan. **The central decision criterion is to determine the most effective options, in terms of cost and performance, amongst conventional grid extension and RE based mini grid or stand alone**

small systems. The mini grid can be completely or partially powered by RE. There can be an option of grid extension with RE based DG deployment. **A generic design framework has been developed** here and applied in Chapter 5. Applying this general framework in specific cases would necessitate addressing several new situations as would have arisen in case to case basis.

Case study in Sundarbans Islands

This chapter reports a case study conducted in the island cluster of Sundarbans where the generic framework is validated for a real island. **Extensive field works have been undertaken in both types, i.e. electrified as well as non-electrified islands. A detailed exercise has been conducted to prepare an electrification plan in two villages within a small island called Bali which is completely non-electrified till now. An approach has been developed where combination of RS / GIS based analysis is integrated into ViPOR, coupled with hourly time series energy modelling with HOMER, to give shape rigorous simulation and analysis in village scale.** Several scenarios have been made considering Diesel, PV, Biomass and PV-Biomass hybrid configurations as power generation units for autonomous mini grid. Biomass electricity generator modules of 10 kW, 20 kW and 40 kW have been developed in HOMER. Some drawbacks of ViPOR model have been identified and rectified for better accuracy. Rudimentary power systems have been designed considering two separate power plants each for individual village and also a central power plant serving both villages. **Sensitivity analyses were performed to experience the behavior of the power system to the effects of changing a few parameters** like load, fuel cost, economic parameters, subsidy, geographic terrain, geographic dispersion of the load points etc. At the present level of technology prevailing in Sundarbans region, biomass gasification is the cheapest energy generation option. However, due to sustainable biomass resource availability and environmental considerations PV-biomass hybrid system is being promoted by the local government. **The total net present cost of electrification is increasing with the increase in energy consumption** in a linear manner. And the levelized cost of energy is decreasing with the increase in energy consumption. A centralized plant instead of two individual plants is cheaper for electrifying the two neighboring villages in the case study. **In low load densities the overall cost per kW is found to be higher**

than that in higher load densities. Cost of energy is decreasing with increase in the load factor. The case study clearly shows that **the levelized cost of energy delivered to the island people strongly depends on the spatial features of the target region and also on the choice of the RE system configuration** besides various economic parameters. The optimum configuration in an autonomous power system changes with the changing value and properties of load demand. This chapter shows that the generic framework for island electrification, as developed in the Chapter 4, can be successfully used for a specific real world situation.

Tariff, business models and impacts

It deals with tariff systems, business models and the impacts of electrification projects as observed in Sundarbans island clusters. **Appropriate tariff structure is one of the key factors for a sustainable electrification project**. Various tariff types which are commonly practiced in India are discussed in this chapter. **Estimation of levelized cost of electricity service over the life span of a project is the basis for tariff rate determination**. **A simplistic energy based tariff structure is exercised for the case study power system in Bali Island**. A discussion on business models also describes the existing systems prevailing in Sundarbans. The last section of this chapter **records the impacts and benefits of existing electrification initiatives** already brought into the island society of Sundarbans. Before early 1990s, the entire region was facing tremendous barriers for development because of the complete absence of electricity service while at present **significant positive changes have been identified**. **Electrification there has been exemplified as a strong mechanism of involving local people.** The impacts of remote island electrification in this region become vital in the efforts towards facing global change through adequate recognition and accounting of human dimensions.

3. Highlights of the study

- ✓ Detailed review type research works have been conducted on selected themes such as ‘distributed generation’, ‘microgrid’, power supply systems, software tools, RS/GIS applications etc.
- ✓ Extensive field works have been undertaken in the island cluster of Sundarbans.
- ✓ A generic framework for island electrification has been developed.
- ✓ The framework has been validated in two neighboring non-electrified villages of Bali Island in Sundarbans. Simulation, optimization and sensitivity analyses have been performed for designing rudimentary power systems. Time series modeling has been done for power generation with hourly resolution considering existing technologies as prevailed in Sundarbans region. Biomass gasification modules have been developed in HOMER environment. NREL’s HOMER + ViPOR combination method has been improved. Time and cost saving approach has been developed with RS/GIS integration with power system modeling.
- ✓ The key impacts of existing electrification projects in Sundarbans have been investigated along with business models and tariff structures.

4. Outlook

Improvement in each sphere of island electrification is a continuous process. There are on-going efforts towards increasing the overall techno-economic efficiency of power systems suitable for electrification of small islands in developing countries. Similarly ‘social engineering’ is being given increasing importance for sustainability of electrification projects in far flung areas. Significant research and development efforts are globally taking place in the managerial aspects in the direction of business models and tariff structures. In the world of modeling too there exist many scopes for improving the accuracy and effectiveness. Some of the limitations of ViPOR model have been identified in chapter 2, for example, which can be overcome in the future. Also, at present

ViPOR does not have the capability to model multiple centralized interconnected power systems. A generic methodology framework for island electrification with optimized renewable energy resources has been developed in Chapter 4 and is applied in one island in Chapter 5. The same framework can be validated and improved, if necessary, by conducting similar studies in other islands of the world. The present research dealt with selected sets of technology options for the case study. Wider coverage of technology choices would make the optimization process more complete for real life situation.

Electrification through renewable energy has brought positive changes in overall development status of the island society in Sundarbans. Many other small islands in developing countries through out the world are holding opportunities for greater deployment of renewable energy based electrification in the near future.

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