Decentralized renewable hybrid mini-grid based electrification of rural and remote off-grid areas of Bangladesh

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Declaration

Part of this thesis has been published in the *Energies* covering the hybrid mini-grid based electrification for the coastal areas of Bangladesh (please see the reference below).

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Abstract:

Like many other developing nations Bangladesh has a very poor electrification rate especially in the rural areas. Millions of people here are excluded from the benefit of globalization because of no access to necessary electricity supply. This research work proposes decentralized renewable hybrid mini-grids as a potential approach for off-grid rural and remote area electrification in Bangladesh. Based on the available renewable resources an area specific resource map has been developed. The characteristics of the bottom of the economic pyramid market including customers' attitude to switch from liquid fuel to mini-grid based electricity supply, expected load demand and their willingness to pay have been explored through a field study. Different combinations of hybrid systems have been designed and optimized using the HOMER micro-grid design software to cover the whole country. Results suggest that serving the required load over wider hours rather than having the same load concentrated in a short span of time can achieve better hybrid system performance. Initial capital subsidy of 40 percent along with 5 percent interest on loan has been applied in accordance with the renewable energy policy of Bangladesh government. Proposed optimized rice husk-diesel hybrid system in Rangpur, micro hydro-PV system in Rangamati, wind-PV system in Chakaria and PV-diesel system in coastal areas can produce electricity for USD 0.172/kWh, 0.291/kWh, 0.217/kWh and 0.316/kWh respectively while serving loads for 12 to 18 hours a day. Field data analysed by applying the dichotomous choice contingent valuation method revealed that customers are willing to pay maximum of USD 0.43/kWh. The value difference between the cost of electricity generation and the customers' willingness to pay creates the opportunity to attract the private investors. Suitable business delivery models have been identified and explained for successful mini-grid business by private investment. Optimum hybrid systems have been standardized for replication and a sustainable business model has been suggested for scaling up this electrification approach.

Acknowledgements

I do possess a dream to empower the rural poor around the world. I realized that people at the bottom of the economic pyramid could not change their lives without having access to basic electricity supply. My dream even got bigger by now and I am working toward fulfilling it.

I am grateful to my heavenly father who seeded the dream in my brain. Thanks are due to my mother, my elder brother and sisters for encouraging me all the times. I am lucky enough to have such a wonderful wife 'Yasmin' who supported me in every steps and my heartfelt love for my four little daughters who always see only my bright sides.

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List of Abbreviations

AC	Alternating Current
ADB	Asian Development Bank
BADB	Bangladesh Agricultural Development Board
BBS	Bangladesh Statistical Bureau
BCAS	Bangladesh Centre for Advanced Studies
BDM	Bangladesh Meteorological Department
BERC	Bangladesh Energy Regulatory Commission
BOP	Bottom of the economic Pyramid
BPC	Bangladesh Petroleum Corporation
BPDB	Bangladesh Power Development Board
BREB	Bangladesh Rural Electrification Board
BUET	Bangladesh University of Engineering and Technology
CCTF	Climate Change Trust Fund
CDM	Clean Development Mechanism
CER	Certified Emission Reductions
COE	Cost of Electricity
CREDA	Chhattisgarh Renewable Energy Development Agency (India)
DC	Direct Current
DER	Distributed Energy Resources
DESA	Dhaka Electric Supply Authority
DESCo	Dhaka Electric Supply Company Ltd.
DFRN	Desert Research Foundation of Namibia
DLR	German Aerospace Centre
DPPL	Dreams Power Private Ltd.
ESMAP	Energy Sector Management Assistance Program
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiance
GIS	Geographical Information System
GOB	Government of Bangladesh
HDI	Human Development Index
HMG	Hybrid Mini-grid
HOMER	Hybrid Optimization Model for Electric Renewables
HPS	Husk Power Systems

IDC	Intelligent Dispatch Controller
IDCOL	Infrastructure Development Company (Bangladesh)
IPP	Independent Power Producers
JAICA	Japan International Cooperation Agency
LCOE	Levelized Cost of Electricity
LGED	Local Government Engineering Department
LPG	Liquid Petroleum Gas
MEF	Ministry of Environment and Forest (Bangladesh)
MG	Mini-grid
MPEMR	Ministry of Power Energy and Mineral Resources (Bangladesh)
MWS	Mean Willingness to Switch
NPC	Net Present Cost
NREL	National Renewable Energy Research Centre (USA)
OECD	Organization for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PBS	Palli Bidyut Samity
PGCB	Power Grid Company of Bangladesh Ltd.
PGEL	Purobi Green Energy Limited
PSMP	Power Sector Master Plan (Bangladesh)
PV	Photovoltaic
RF	Rafiki Power
RAPSS	Remote Area Power Supply System (Bangladesh)
RE	Renewable Energy
REB	Rural Electrification Board (Bangladesh)
REN	Renewable Energy
RERC	Renewable Energy Research Centre (USA)
RET	Renewable Energy Technology
RHMG	Renewable Hybrid Mini-grid
RMG	Renewable Mini-grid
SDG	Sustainable Development Goal
SEDA	Sustainable Energy Development Agency (Bangladesh)
SHS	Solar Home System
SPARRSO	Space Research and Remote Sensing Organization (Bangladesh)
SWERA	Solar and Wind Energy Resource Assessment
TESco	Tsumkwe Energy Supply Company (Namibia)
TIS	Technological Innovation System
Tk	Tk (Bangladeshi Currency)

UNDP	United Nations Development Program
UNEP	United Nations Environment Program
USD	United States Dollar
WBREDA	West Bengal Renewable Energy Development Agency (India)
WERM	Wind Energy Resource Mapping
WTP	Willingness to Pay
WTS	Willingness to Switch

Chapter 1

Research Background

Chapter Highlights

This chapter presents a bird's-eye view of the global energy scenario, transition of conventional energy usages towards renewables and explores the energy situation in Bangladesh while identifying the country's hurdle in achieving its target of '*energy for all by 2021'*. Subsequently, it proposes renewable energy generation in a decentralized mode for rural Bangladesh and explores the knowledge gap in this approach. Specific research questions have been identified followed by a core literature review to highlight the rationale of the research. Finally it presents the snapshots of the methodologies applied in the following chapters.

Chapter 1

1 Background

1.1 Energy and Development

Moving from the ancient farm based economy to the modern industrialized society, human civilization has experienced a three thousand year of journey towards steam engine until the recent decades and the sophisticated steam turbine of today (Smil, 2004). Hence, energy has been claimed as a major prerequisite for development. It is evident from the recent global history that countries lacking the basic energy availability and its applications are backtracked in the race of social and economic development. For the developing countries energy consumption and socio-economic developments are closely related. Different studies reported unidirectional causality between energy consumption and economic growth in developing countries like South Africa (Ziramba, 2013), Bangladesh (Bin Amin and Rahman, 2011), China (Archibong, 2011), Kenya (Odhiambo, 2010), India, Indonesia (Asafu-Adjayel, 2000), Pakistan (Atif and Siddiqui, 2010) and Vietnam (Binh, 2011). Bidirectional causality is also reported for many countries like Algeria (Ziramba, 2013), Iran (Nonejad and Fathi, 2014), Thailand (Asafa-Adjayel, 2000), Sri Lanka (Morimoto and Hope, 2004), Tunisia (Abid and Serbi, 2013) and Kuwait (Shaheet, 2014).

Consumption of all forms of energy is much higher among the developed nations than most of the developing countries (Table 1.1). Per capita energy consumption in Canada and USA is about twenty times higher than Nepal and Sudan and around thirty times higher than Bangladesh. However, a country being rich in energy resources does not always reflect that the country is necessarily rich in energy consumption. For example, although Nigeria ranked as the 14^{th} largest reserve of energy (oil and gas) with a 37.2

billion barrel of oil and 182 trillion cubic feet of natural gas reserve (WEC, 2013) its per capita energy usages is relatively very low which only changed from 577koe (kg of oil equivalent) to 773koe during the period of 1971 to 2013. On the other hand, during the same period (1971-2013) Chinese energy consumption increased from 465koe to 2,226koe. Contrarily, Sub-Saharan Africa constitutes around 30% of the global oil and gas discovered during the last decade, however electrification rate in this region remains one of the lowest in the world (IEA, 2014). Making reliable, affordable and usable energy (can be referred as exergy) readily available to its entire citizen is crucial for socio-economic development of a country.

Country	Consumption	Country	Consumption	Country	Consumption
United States	6917.4	Canada	7247.2	UK	2751.6
Germany	3749.1	Australia	5484.7	Japan	3570.4
Russia	5093.1	South Korea	5262.0	China	2226.3
Denmark	2903.7	Kuwait	9757.4	France	3839.9
Brazil	1437.8	Bangladesh	215.5	India	606.1
Nepal	369.7	Sri Lanka	487.5	Nigeria	773.0
Ethiopia	507.0	Ghana	343.6	Sudan	374.8

Table 1.1: Per capita energy consumption (kg of oil equivalent) in different countries between 2013 and 2014 (Source: World Bank, 2014:1)

Being the most crucial element for development exergy has been the driving force for the modern globalized economy and the world has experienced a staggering 157% increase in consumption between 1970 and 2013. During this period global energy consumption rose from 104mboe/d (million barrels of oil equivalent per day) to 268mboe/d and most of the increased consumptions were made by the developing nations due to their higher GDP growth (Byer and Özel, 2014). Rapid industrialization and urbanization along with population growth and increase in national income in many developing nations like China, India, Brazil, Malaysia etc., contributed to almost 500% increased energy consumption in compare to the OECD countries where demand only increased by 69%. However, according to Oxford Energy (2016), the difference in energy consumption between the OECD and non-OECD countries is still significant while the consumption remains almost constant in the OECD states against significant annual growth in the rest of the world.

The rapid pace of socio-economic development and positive HDI (Human Development Index) changes across many parts of the developing world over the last twenty years happened through the revolution of information technologies (UNDP, 2015). These changes created the growing demand of electricity that is faster than the 'total primary energy supply' (WEC, 2013). Affordable supply of electricity, the major form of converted energy is vital for economic growth (Tucker et al. 2014). Significant relationship between increased electricity consumption and growth of gross domestic product (GDP) has been established beyond any argument (Bayer and Özel, 2014). A one percent growth of electricity consumption by the emerging nations results in substantial increments in their economy (Table 1.2). Per capita increased electricity consumption directly stimulates rapid economic growth and indirectly enhances social development especially in the case of countries reflecting low and medium Human Development Index (Leung and Meisen, 2005 and Masuduzzaman, 2012).

Country	Low estimate	High estimate
Brazil	0.39	0.42
China	0.22	0.25
Indonesia	0.14	0.19
India	0.22	0.25
Philippines	0.27	0.29
Thailand	0.41	0.43
South Africa	0.41	0.44
Peru	0.38	.041
Malaysia	0.29	0.31

Table 1.2: Impact of a 1% increase in electricity consumption on economic growth (Source: Byer and Özel, 2014)

1.2 Global Shifts Towards Renewables

Coal, oil and natural gas historically dominated the energy market. Global oil price hike in the recent past and the massive downfall of price since the second half of 2014, when the market experienced a significant price change from +USD100/b in June 2014 to ±USD44.3/b in Jan 2015 (OPEC, 2015) indicate the volatility of the oil market. Despite the predicted upward trend of oil price (Figure 1.1) many countries i.e., India, Indonesia, Egypt, Malaysia, Morocco, Ghana, Angola and Tunisia etc., have abolished major liquid fuel subsidies either in full or in part as trend of global energy market shifting to an extent towards renewable resources. Energy market has been predicted to have a sharp increase in application of renewable resources (i.e., solar, wind) for electricity production in the near future (Figure 1.2).

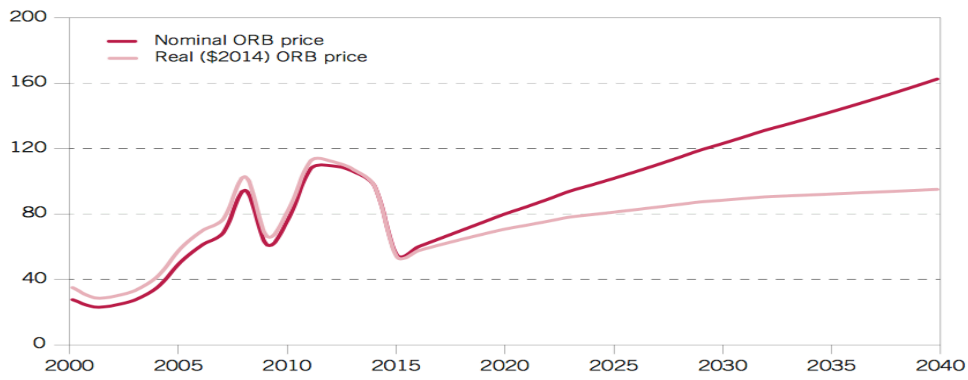


Figure 1.1: Recent oil price and future price assumption (USD/barrel) as OPEC reference basket (OPEC, 2015)

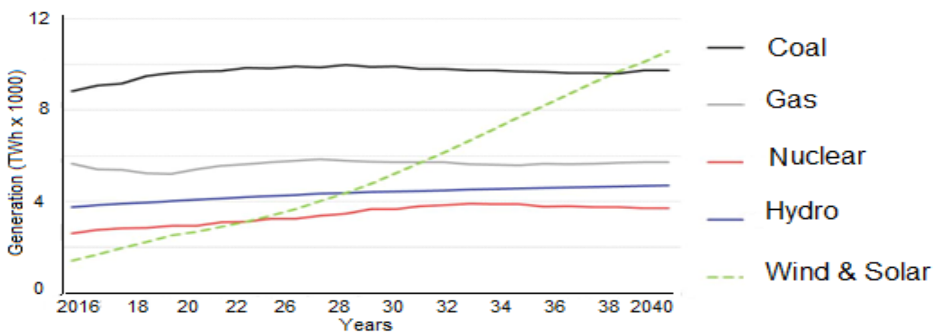


Figure 1.2: Major electricity generation (thousand TWh) resources global trend (Source: Bloomberg, 2016)

While nearly two hundred countries signed 'Seventeen Goals of 2030' agenda for sustainable development and '*Paris Climate Change Agreement*', the energy market in 2015 had a record total investment of around USD 286 billion in renewable technologies which is almost six times higher than the amount invested in 2004 (UNEP, 2016). The impressive growth of two major renewable sources, solar and wind over the other renewable technologies is the result of recent price fall of these technologies in the global market, significant developments in technical knowhow and finally suitable policy initiatives by many countries. Moreover, IRENA (2016) predicted a further sharp decline in price of solar and wind based power generation by 2025.

1.3 Energy for Developing Nations

Despite remarkable achievements in many critical aspects of the human development index (Human Development Report, 2014:1), around 1.2 billion people still have no access to basic electricity in the developing nations (IEA, 2016). Many countries around the world have been suffering from the lack of energy availability to meet their growing consumption. Good GDP growth in some developing nations increased their appetite for higher energy demand (Source: EIA, 2016). Following the relocation of industries and services from the OECD and newly industrialized countries to the lower cost developing nations, energy consumption has increased in many emerging economies. Almost half of the increase in global demand in energy by 2030 will be for power generation, a major share of which will be result of rapid growth in some Asian economies (UNEP, 2016).

While trying to cope with the basic access to energy, developing nations have to deal with their existing poor infrastructure, inadequate policy initiatives and lack of available investments. Insufficient capitalization and investment capabilities coupled with suboptimal management and low tariff supported by short-term political motivations are considered as common problems in this sector in many countries. During the1990s historically state owned electricity sectors in many countries faced vigorous reform to attract private investments (Khanna and Rao, 2009). Some developing countries followed the classical example of the United Kingdom by fostering private investment for independent power generation facilities. Chile pioneered the power sector reform in the late 1980s as the first developing nation and China was the second doing so. This trend was later followed by many other developing nations.

The diffusion trend of increased electrification differs among different regions, which is evident from the fact that access to electricity by the lower income level people in Asia and Latin America is taking place at a quicker rate than in Africa (Rujiven et al., 2012). However, very poor electrification rate of 18.2% in Uganda, 15.3% in Tanzania, 31% Togo, 55% in Nigeria, 31.1% in Cambodia, 59.6% in Bangladesh (World Bank, 2016) and similar poor rates in many other countries remain as the major challenge for poverty alleviation.

1.4 Bangladesh energy situation

Bangladesh, one of the emerging countries in South Asia aims to attain the 'middle-income country' status by 2021 (Muzzini and Aparicio, 2005; BBS, 2015), and has already gained considerable success in ticking many human development indicators in the recent years. The country aims to supply reliable and affordable electricity for all by 2021 (Planning Commission, 2012; BPDB, 2015). However, the nation is still suffering from acute shortage of reliable supply of electricity especially in the rural areas. A recent study revealed clear positive relationship between energy consumption and economic growth for Bangladesh based on related data analysed from 1994 to 2004 (Asaduzzaman and Billah, 2006). The same study confirmed that increased energy usages here led to higher socio-economic growth.

Bangladesh managed to continue its growth (in agriculture, industry, services etc.) despite the recent global financial downturn as the GDP was 6.1% in 2015 and it was expected to be 6.5% in 2016 (Figure 1.3). Improved national macroeconomic factors helped in increasing installed generation capacity in the power sector in the recent years. Although the country's electrification rate rose from 40% to around 60% between 2003 and 2013, supply remains mainly urban oriented and still very unreliable (ADB, 2015).

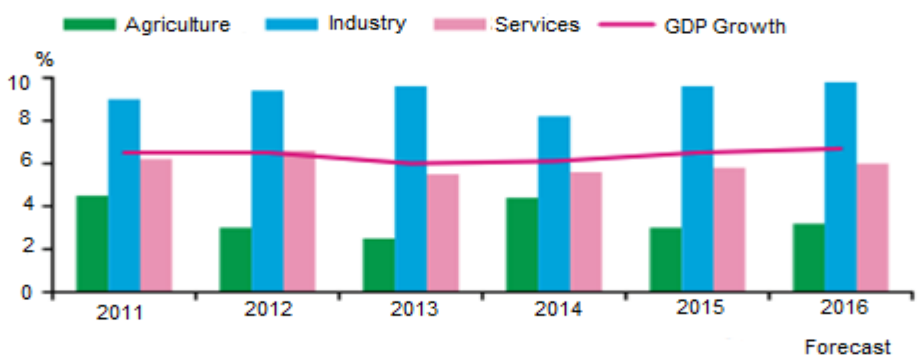


Figure 1.3: Overall GDP Growth and growth by sector (BBS, 2015)

During the last two decades Bangladesh experienced a sharp rise in energy consumption. This trend has been projected to intensify in the upcoming years as the nation's economic growth is continuing. In reality, around 11.5% of the national industrial production currently is hampered in Bangladesh due to unreliable power supply including power outages (Srivastava and Misra, 2007 and ADB, 2015). Notably, the whole power sector is subsidized to a great extent (Table 1.3) and almost all the state owned power sector entities are facing huge financial losses (Figure 1.4).

Energy Products		FY 2010	FY 2011	FY 2012
Subsidies on electricity (million US$)	Generation Level	77.30	612.82	832.57
	Distribution level	26.70	71.27	208.21
	Total	104.00	684.10	1040.78
Subsidies on petroleum products (million US$)	Total	23.88	951.65	892.39
Total energy subsidies (million US$)	**Total**	**127.88**	**1635.74**	**1933.17**
GDP at current market price (million US$)		90171.95	103468.1	119239.1
Energy subsidies (on and off budget) as % of GDP		***0.14***	***1.58***	***1.62***

Table 1.3: Energy subsidies in Bangladesh (Source: Mujeri, et al., 2013)

Figure 1.4: Profit and loss by state owned power sector enterprises of Bangladesh (Source: Modified from Ministry of Finance, 2015).

According to the Power System Master Plan 2012 (BPDB, 2012:1) the country should have installed generation capacity of 16,000MW by the year 2016; whereas as of September 2016 maximum generation capacity of only 8,177 MW was evident (BPDB, 2016). To meet the growing demand of power generation, transmission and distribution capacities need to be extended in a sustainable manner. However, Bangladesh's present and future strategic energy mix is mainly fossil fuel based (Table 1.4). Natural gas and oil account for most of the primary energy mix in Bangladesh (IEA, 2012 and Gomes, 2013), while coal only serves around 2% (BPDB, 2016). However, there are some large coal based power plants either under construction or under serious considerations (Table 1.5) and in the near future coal will take the major role in the energy mix.

Energy	Bangladesh			Global	
	2011	2016*	2021	2011	2030
Gas	87.5%	60.10%	30%	18%	28%
Oil	6%	31.25%	3%	10%	5%
Coal	3.7%	1.88%	53%	37%	38%
Hydro	2.7%	1.71%	1%	17%	4%
Nuclear	0%	0%	10%	17%	19%
Renewables	0.5%	0.6%	3%	1%	6%

Table 1.4: Energy mix in Bangladesh compare to global position (Source: Planning Commission, 2012 and *BPDB, 2016)

Project	To be implemented by	Capacity (MW)
Maitree Super Thermal Project, Rampal	Bangladesh-India	1,320
Matharbari Super Coal Power Plant	Coal Power	1,200
Payra Thermal Power Plant, Potuakhali	Nowpajeco	1,320
Pakua Power Plant	EGCB	1,200
Moheskhali Power Generation Plant	PDB & Malaysia	1,320
North Bengal Thermal Power Plant	APNCL	1,320
700MW Coal Power Plant	Bangladesh-Singapore	700
G2C Power Plant	Bangladesh-S. Korea	1,320
PDB CHDHK Power Plant	Bangladesh-China	1,320
Munshiganj Power Plant	RPCL	350
Total		**11,370**

Table 1.5: Proposed coal based power plant of Bangladesh (Source: BREB 2016)

According to MPEMR (2015) Bangladesh has an estimated reserve of 3.3 billion tonnes coal, 12.5 Tcf natural gas and 28 million barrels of oil. However, only one coal deposit of the country with a capacity of 1 million tonnes per year has been developed since 2005 out of five deposits (Gomes, 2013). Very limited indigenous fossil fuel reserves coupled with poor bureaucratic administration and an inefficient mining policy framework make the utility scale investment in power sector unattractive for corporate investors.

Government has been introducing many implicit and explicit policies since 2005 (Mondal, et al., 2010) to achieve its '*electricity for all by 2020'* target (PSMP, 2005). The overall achievement in the power sector of the country during last seven years (from 2009 to March 2016) has not been promising enough (Table 1.6) to make the ambitious target of PSMP (2005) a real success.

Indicators	Status before 2009	Status by March 2016	Achievement
Installed capacity Max. (MW)	4,942	14,429*	+9487
Maximum generation (MW)	3,268	8,177	+ 4,909
Total distribution line (km)	2,60,000	3,72,000	+1,12,000
Renewable sources (MW)	1.6	200	+198.4
Population served (%)	47	76	+29
Per capita consumption (kWh)	220	371	+151
Number of connections	10,800,000	20,400,000	+96,00,000

* 2,200MW of captive generation included

Table 1.6: Government's achievement in power sector during last seven years. (Source: BREB, 2016)

The huge gap between current generation status (8177MW) and government's ambitious generation target of 24,000MW by 2021 for universal access of electricity in a course of next five years is a serious challenge. Moreover, the government has set a capacity building target of 48,538MW and 59,697MW by 2031 and 2041respectively, which includes 6,500MW of electricity to be imported from neighbouring India (BREB, 2016). Most of the planned power plants are fossil fuel based as the country aimed only for 10% electricity from the renewable resources. Renewable energy initiatives of the energy master plan include 3,100MW generation from the available renewable sources by 2021, of which 1,100MW to be contributed by the public sector and the rest 2,000MW by the private sector (BREB, 2016).

1.5 Mini-grid Electrification for Rural Bangladesh

The SDGs (Sustainable Development Goals) cannot be achieved by 2030 without a rapid progress on the SDG7, which ensures affordable and secure access to sustainable energy for all. Only 50% electrification rate in rural Bangladesh against 90% in the urban areas raised the concern among policy makers regarding the socio-economic development of the 80% of the total population of the country living in villages (World Bank, 2014).

The BREB (Bangladesh Rural Electrification Board) a subsidiary of the Bangladesh Power Development Board (BPDB) was formed in 1972 to supply electricity to the rural areas. Since then BREB has achieved moderate success and grown in to 77 'Palli

Bidyut Samitys' known as PBS (operating co-operatives) across the country with a limited coverage and had positive socio-economic impact on rural lives (BREB, 2011). BREB partially covered 416 upazillas (sub-districts) out of 490 through the Palli Bidyut Samitys till March 2016 (BREB, 2016). However, because of insufficient grid extension, poor quality electricity, unreliable supplies, massive load shedding and organizational corruption this institution failed to achieve its strategic goal. As a result many areas of the country remain unelectrified (Figure 1.5). Under the current circumstances many rural consumers do not have any possibility of being connected to the national grid in the foreseeable future through the BREB.

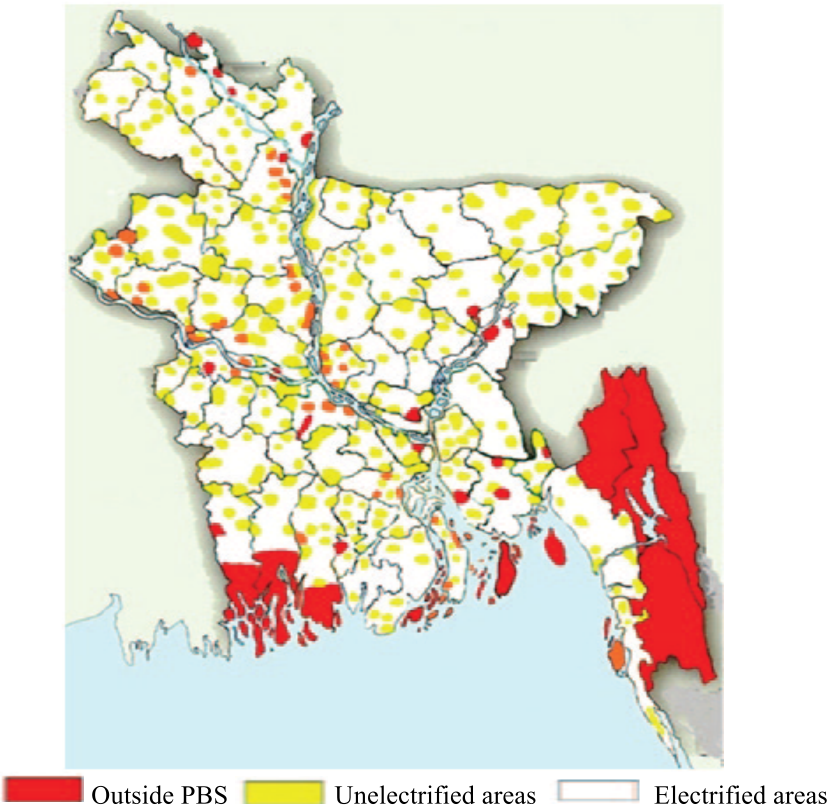


Figure 1.5: Electrified and non-electrified areas in Bangladesh
(Source: IFC, 2014)

An ever-increasing supply and demand gap in the electricity sector encouraged the government to promote electricity from renewable resources especially in rural areas. Considering poor investment capability, limited natural resources, volatility of fossil fuel price and global environmental concerns, distributed electricity generation initiatives have been introduced in the 'final national energy policy 2008' as the Renewable Energy Policy of Bangladesh (2008). According to this policy "*renewable* *resources will contribute 5% of the total generation capacity by 2020 and 10% by 2030"*. Policy induced and subsidy based Solar Home Systems (SHS) achieved the most remarkable success in this sector, which achieved the installation milestone of 4.5 million units by March 2016 in rural Bangladesh (BREB, 2016). However, high initial investment (considering the rural economic conditions), very limited operating hours (only few hours in the evening), poor quality of light, expensive repair and maintenance, lack of quality service standards and very high unit cost of electricity from SHSs created a unique scope for decentralized renewable mini-grids to serve this huge rural market (Mondal, et al., 2010). Benefits of such mini-grids over standalone SHSs are well evident in many literatures (Hazelton, et al., 2014; Bhattacharyya and Palit, 2016; Knuckles, 2016; Ulsrud, et al. 2011; Blum, et al., 2015; Chattopadhyay, et al., 2015; Yadoo and Cruickshank, 2012; Azimoth, et al., 2016; and Dada, 2014).

The rationale for renewable energy (REN) can be particularly suitable for developing countries like Bangladesh. For instance, for some rural and remote areas, transmission and distribution of energy generated from fossil fuels is difficult and expensive considering the current economic situation of Bangladesh. Distributed generation of renewable energy i.e., hybrid mini-grids can serve independently the requirements of locals as an effective alternative to grid extension. Interest in renewable energies has increased in recent years due to environmental concerns about global warming, reduced costs of renewable energy technologies, and improved efficiency and reliability (Azimoth, et al., 2016; Blum, et al., 2015). Poverty alleviation by renewable energy projects in many developing countries has been successful by creating businesses and employment. Unfortunately, diffusion of such renewable based mini-grids is still very slow in Bangladesh.

There are only a few successful renewable mini-grids to meet the economic perspective as well as consumer satisfaction in the developing countries. Studies (Chowdhury, et al. 2015; Lowe and Lloyd 2001; Sivarasu, et al. 2015; Kenfack, et al., 2014 and Chattopadhyay, et al. 2015) identified several reasons for the mini-grid failure around the world, i.e., lack of detailed market information, inadequate dissemination, inappropriate system design, application of wrong investment tools, lack of integration between supply and demand, inappropriate tariff design, failure to encourage productive income generation and poor policy framework to address existing barriers.

These issues have been discussed in detail in the subsequent chapters of this research work and sustainable solutions designed for Bangladesh by answering specific research questions.

1.6 Research Questions

Despite having an abundance of renewable energy resources, especially solar, wind and biomass besides the huge demand for electricity at the village level, diffusion of decentralized hybrid mini grids in Bangladesh is still at a very initial stage. Moreover, this distributed renewable energy generation approach has lost its momentum because of the failure of some mini-grids in Bangladesh in recent years (discussed in chapter 5). Although off-grid rural electrification through stand-alone solar home systems (SHS) has achieved a strong market penetration, the limitations and drawbacks of this technology have created a clear demand in the market for a better proposition. Apparently renewable hybrid mini grids could be the right option to resolve these issues.

Different studies on hybrid mini-grid electrification for Bangladesh (Bhattacharyya, 2015; Chowdhury, et al., 2015; Nandi and Ghosh, 2009 & 2010; Khan, et al., 2016; Khan and Huque, 2012) described the suitability of this approach for supplying electricity in remote and rural areas. Most of these studies are not conclusive, as these are very area specific and are not applicable to all non-electrified areas having different renewable resource abundance across the country. Moreover, none of these studies either explored the actual consumer demand or the addressed the ability and affordability of poor rural people. However, a dynamic approach has been missing among the public and private utilities and private actors in Bangladesh in applying renewable distributed mini-grid electrification as a tool to achieve the SDG7 towards government's universal electrification target by 2021.

Design and implementation of hybrid mini grid(s) serving different geographical locations with a variety of resource combinations are not simple tasks. Multiple dimensions of available renewable energy resources, i.e., seasonal and diurnal availability, suitable technology acquisition, consumers' need, ability and affordability to pay along with local socio-economic conditions and inevitably the demand and supply side managements are the major factors that need to be addressed.

Therefore, this study looks in-depth to find the right approach to establish mini grids as a solution to deal with the existing power crisis in off-grid areas while transforming the local socio-economic trend into a better shape. For this purpose the following research questions have been investigated in this research work:

1. What would be an appropriate configuration of mini-grid models (in terms of size and resources mix) for rural Bangladesh from a techno-economic perspective?
2. What will be the suitable business model and financing mechanism (for initial investment, operation and maintenance) to make the appropriate models of mini grids sustainable for private investment?
3. Can the suitable techno-economic models of mini-grid(s) be standardized for replication to obtain economies of scale?

By answering these questions this research work proposes suitable techno-economic hybrid mini-grid models for rural Bangladesh to achieve its target of electricity for all in a sustainable manner.

1.7 Core literature review

Supplying the people of Bangladesh in rural areas with basic and reliable electricity is a critical demand of the time. The multidimensional challenges of centralized electricity access initiatives have been evident in many official documents (ESMAP, 2005; BPDB, 2008 and ADB, 2013) and literature (Barnes, 2007; Palit and Churey, 2011 and Taniguchi and Kaneko, 2009). Limited financial capability of the government, reliance on aid based financing, heavily subsidized generation and supply of electricity and finally the mismatch between the *central supervision and local operation of rural electrification strategy* are described as major hurdles in the official documents cited earlier. While Barnes (2007) indicates lack of integrated expansion of the Rural Electrification Board (REB) including the Palli Bidyuit Samity (PBS) along with the poor national generation capacity as the reasons for the failure of the centralized rural electrification approach, Palit and Churey (2011) highlight slow national economic growth, poor demand by the rural households and REB's unrealistic strategic targets (revenue per km of distribution line, cost of service etc.) to be the failure factors in this context. Moreover, analysing the performance of REB in rural electrification based on all the associated driving and restraining factors, Taniguchi and Kaneko (2009) found political interference as having a vital negative impact.

Considering the poor performance of the centralized rural electrification approach, different decentralized renewable electrification initiatives i.e., Solar Home Systems (SHS), Solar Irrigation Project, Biogas based power generation etc. have been in practice since the early 2000 as alternatives (IDCOL, 2015) and later in 2002 and 2008 the initiatives have been supported by the new renewable energy policy of the country (Renewable Energy Policy of Bangladesh, 2002 & 2008). The ADB (2015) reported Bangladesh to be the pioneer in implementing SHSs as a renewable electrification tool for rural areas. However, the same report explored different challenges in the market in recent years. These are the high cost of frequent battery replacements, poor aftersales services and finally unregulated traders with low quality technology supply. Hybrid mini-grids have been employed as a more sustainable alternative to standalone energy systems (i.e., solar home systems) in many countries (IRENA, 2015; ELFORSK, 2006; Opiyo, 2015 and Azimoh, et al., 2016). Transition from SHSs to hybrid mini-grids has been discussed elaborately in various reports and literatures (Ulsrud, et al., 2011; Bhattacharyya, 2013; Chattopadyay, et al., 2015; ACTFCN, 2015; ELFORSK, 2006 and IED, 2013). Decentralized renewable mini-grids have been widely studied for poverty reduction and social empowerment by many authors. Yadoo and Cruickshank (2012) studied poverty alleviation in Nepal, Kenya and Peru through mini-grid electrification. Alfaro and Millar (2014) showed rural empowerment in Liberia as a result of renewable mini-grid application. Several reports identified socio-economic developments in rural India with the expansion of mini-grid electrification (GNESD, 2014 and Narula and Bhattacharyya, 2017). Similarly social developments related to mini-grid in South Africa have been reported by Azimoh et al., (2016).

Bangladesh followed the footprint of some successful initiatives in implementing decentralized hybrid mini-grids by different countries in the recent years (Alam and Bhattacharyya, 2016). IDCOL (Infrastructure Development Company Limited) has been trying to attract private investment in this sector by applying renewable energy policy instruments (BPDB, 2015). However, only a few mini-grids have been implemented in Bangladesh so far and Khan, et al., (2016) reported only one private investment project that is still running successfully. Very few published data are available regarding the existing and proposed hybrid mini-grids and neither market data nor policy analysis have been carried out in Bangladesh to identify the actors and factors impeding the growth of such renewable technologies.

Mortiz (2012) highlights the importance of policy driven diffusion of distributed mini-grids while the private sector's global competitive edge is protected by the local policies. Pandey (2001) emphasized understanding of past and current trends of policy regime and dynamics of socio-economic patterns of a country for sustainable future policy modelling. Historically various institutional and economic barriers such as poor governance, inefficiency of public sector, underdeveloped financial institutions, trade barriers and poor market information have been identified as the major hindrance for the sustainable renewable energy policy implications in developing countries (Abdalla, 1994). 'Renewable energy policy 2008' offers substantial investment subsidies for decentralized renewable energy based electricity generation in Bangladesh. Lee and Shih (2011) focused on addressing the burdens of financial incentives (i.e., subsidy) on the economy while modelling the policy to implement such renewable energy generation technology approaches. Researchers (Reuter, et al., 2012 and Zhang, et al., 2014) applied economic models to explore the uncertainties while presenting precise information on financial points of investment in this sector. However, Pandey (2001) argued that regardless of the type of policy modelling (either top-down or bottom-up) energy sector in some developing countries i.e., Brazil, China, India experienced considerable inflow of private capital including foreign investment as a result of integrated deregulation and privatization. Simultaneously bottom-up energy policy models with optimization elements have been used by many developing countries, which reflect the government controlled centralized markets (Shukla and Kanudia, 1997).

Utility scale renewable energy investment and operational risks and risk management studies are well evident (Sadrosky, 2012; Ritcher, 2012 and Schäfer, et al., 2011). Comparatively there are only a few studies (Morris and Kirubi, 2009; Terrapon-pfaff, et al., 2014; Bhattacharyya, 2013 and Mondal, 2010) around the world identifying the associated risks and exploring the risk managements for mini-grid projects in developing countries. There are handfuls of studies focusing on the techno-economic analysis of decentralized hybrid mini-grids in Bangladesh (Nandi and Ghosh, 2009 & 2011; Khan and Huque, 2012; Bala and Siddique, 2009; Bhattacharyya, 2015; Chowdhury, et al., 2015 and Alam and Bhattacharyya, 2016). However, only few literatures (Mondal et al., 2010; Uddin and Taplin 2009) are available focusing on drivers, barriers and policy aspects of mini-grid electrification in rural Bangladesh. All such studies carried out in relation to Bangladesh are based on theoretically assumed electricity load data and thus these studies miss the potential variations in diurnal and seasonal demand profile. Most of the studies have applied the single choice of resources combination for a nominated location. This approach usually lacks the competitive share of renewable resource mix, which could affect the sustainability of a hybrid system in long run. None of the decentralized hybrid mini-grid studies in Bangladesh have considered the standardization of any area specific hybrid system for replication and the sustainable business delivery models and scaling up issues are yet to be explored.

The present study attempts to fill the above knowledge gaps in decentralized hybrid mini-grid implementation for rural and off-grid remote areas of Bangladesh by answering the research questions.

1.7 Methodologies followed

To answer the research questions this research work investigated all the core areas related to decentralized renewable mini-grid based electrification in Bangladesh, which finally supplement the knowledge gap in this aspect. In the first step clear pictures of available renewable energy resources that can be used in small-scale off-grid mode across the country have been identified (Chapter 2). Thereafter, a detailed field study has been carried out to explore the market characteristics along with rural people's energy requirements and their willingness to pay for such electricity (Chapter 3). Based on the resource assessment and customer's expected load profile optimum hybrid mini-grid systems have been designed and analysed (Chapter 4). In the final step, appropriate business model(s) and financing tools for the selected optimum hybrid systems have been suggested (Chapter 5). Brief illustration for each methodology has been presented below (Figure 1.6 – 1.9).

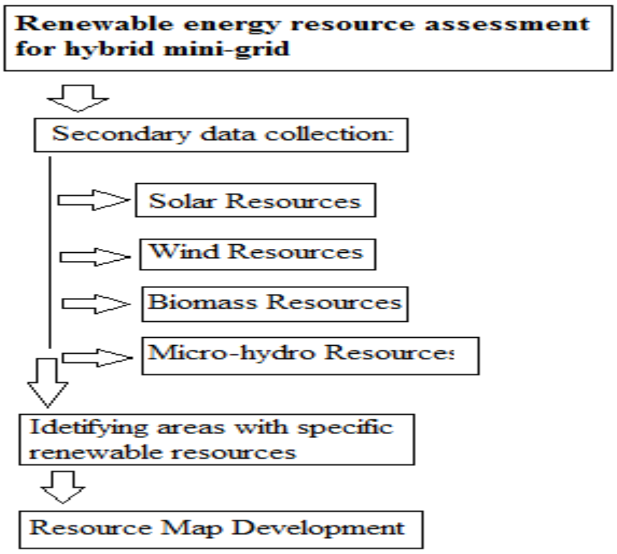


Figure 1.6: Flowchart for renewable resource assessment

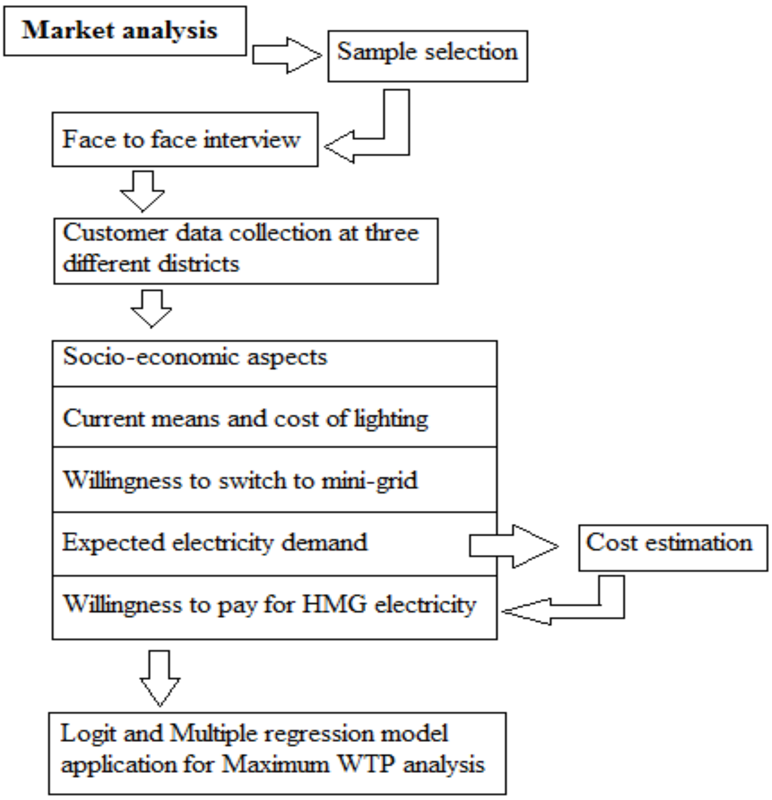


Figure 1.7: Flowchart for market analysis

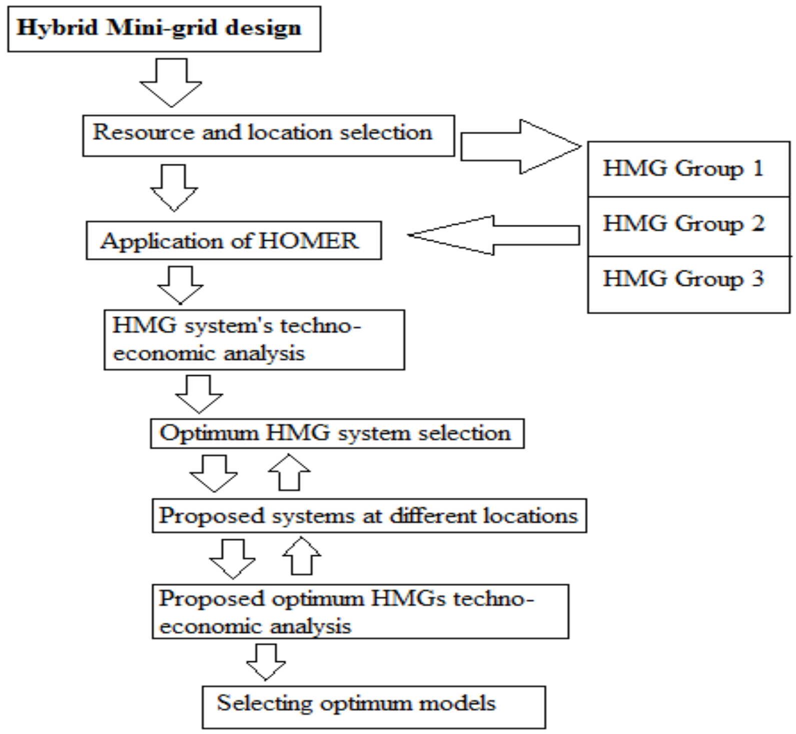


Figure 1.8: Flowchart for renewable hybrid system design

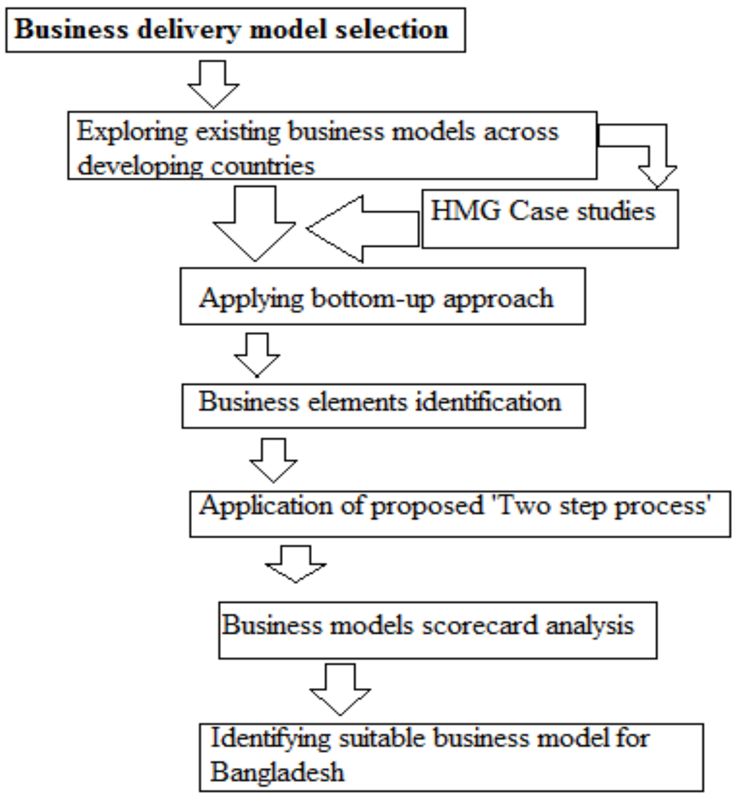


Figure 1.9: Flowchart for business model for renewable mini-grid selection

All the findings through this study that fully answer the research questions have been presented in the final chapter (Chapter 6). Standardization of suggested hybrid systems and probable scaling up opportunities are also highlighted. The possible areas for further research are also indicated in the concluding chapter.

Chapter 2

Prospects of Hybrid Mini-grids in Bangladesh

Chapter Highlights

This chapter identifies prospects of distributed renewable hybrid mini-grid electrification in Bangladesh based on the existing rural electrification status. While identifying renewable energy resources across the country, this chapter builds a resource mapping to assist in designing area specific optimum resource based mini-grids.

Chapter 2

2 Prospects of Hybrid Mini-grid in Bangladesh

2.1 Introduction

Per capita electricity consumption are only 293 kWh a year in Bangladesh and the country ranked 168th in the world as of 2013 (World Bank, 2014:1). However, the Bangladesh Rural Electrification Board (BREB) claimed an increased current consumption to 371kWh due to some effective reform in the power sector (BREB, 2016). Installed generation capacity has increased from 5600MW against the peak demand of 7500 MW (BPDB, 2012:1) in 2012 to 8890MW against peak demand of 9446MW in 2016 (BPDB, 2016). Periodic maintenance of existing power plants, frequent breakdown of aged plants, irregular gas supply, limited seasonal availability of water for the only hydroelectric project and huge system loss contribute around a total deficit of 20% in regular supply. Severe electricity shortage is considered as a key bottleneck for the desired GDP growth of the country as the power outage results in an annual industrial output loss of more than USD 1 billion (World Bank, 2014:2). Untapped growth potential of the rural economy due to non-availability of electricity has not been studied yet in Bangladesh.

The Bangladesh Power Development Board (BPDB) estimated the future energy demands in accordance with the energy policy of the country and projected the electricity demand as 11,794MW in 2020 against a growth rate of 6% but for a higher growth of around 8% it would be 17580 MW (BPBD, 2012:2). The government's plan to achieve 24,000MW of installed capacity by 2021 to provide *electricity for all* is a tough challenge as the power sector currently is almost entirely dependent on natural gas and oil. Bangladesh is currently confronting a regular shortage of indigenous natural gas to supply the existing power plants and household gas supply is going to be replaced by imported LPG (liquid petroleum gas) gradually as part of the government plan to support the power sector. Moreover, nearly 400-800 MW of power would not be available due to plant aging by 2020 (BPBD, 2012:2 and Power Division, 2011:1).

To sustain the expected GDP growth by minimizing the serious gap between demand and generation the government entered into contractual agreements for costly short term solutions, such as rental, quick rental power plants and small independent power producers (IPP) between 2009 and 2012, most of which are based on either imported diesel or furnace oil. This situation has imposed huge fiscal pressure on the government. Strategically, available supply and consumption of electricity are mainly urban and sub-urban oriented prioritizing large industrial loads, leaving most of the remote and rural areas with very disproportionate access to the national grid. While only 40% of rural households have access to grid electricity (World Bank, 2014:2) supplied by REB covering 47,000 villages out of total 87,000 in the whole country frequent and prolonged power cuts are regular here. For most rural people life nearly turns standstill after sunset.

The conventional approach of grid extension and electrification in many rural and remote areas (i.e., some coastal areas, islands, hilly areas of Chittagong hill tracts and many other distant villages) is very difficult and expensive for the Bangladesh government as many non-electrified settlements are commonly dispersed in nature, crisscrossed by rivers, prone to serious seasonal floods and in hilly terrains. As an alternative approach, the government planned to produce a total of 2580MW electricity from solar parks and wind farms by 2021 (PSMP, 2016). However, no real integrated strategic initiatives have yet been taken to realize such a target. Therefore, this chapter investigates the hybrid mini-grid electrification status across the developing countries and explores the availability of potential renewable energy resources in Bangladesh that help the design and implementation of suitable hybrid mini-grid systems in the subsequent chapters.

2.2 Decentralized Mini-grids as Rural Electrification Option

The fastest diffusion of SHS in Bangladesh (World Bank, 2013, IDCOL, 2015; BREB, 2016), which represents generation capacity of 115 MW in 2016 (BREB, 2016) (an increase from 94 MW in 2013 (Hamid, 2013)), has been promoted in the market by using different financial incentives like subsidies, soft loans and instalment payment schemes through micro credit etc. However, there is no actual power generation or economic performance data available, while the quality of electricity produced by the SHSs and the daily available quantity restrict the users from the benefit of modern electricity. The average size of SHSs varies from 30Wp to 50Wp in Bangladesh (IDCOL, 2013). As the demand of electricity increases at the family level with the course of time, adding additional unit or the extension of capacity of the existing SHS is not cost effective. The subsidized unit cost of electricity produced by SHS has dropped from USD 0.8 per kWh (Khan and Khan, 2009; Hussain, et al., 2011) to USD 0.50/kWh between 2009 and 2015 (ADB, 2015). Even with the recent global price fall of solar PV panels this range of unit cost of electricity is considered very high by any standard.

Traditional mini-grids powered by diesel generators have been serving off-grid households and businesses in different parts of the world. Martinot, et al., (2002) reported 60,000 mini-grids in China and several thousands in India, Nepal, Vietnam and Sri Lanka. However, the literature does not clearly indicate whether these existing mini-grids are just diesel based or are integrated with renewable energy technologies (RETs). However, Palit (2012) and Kansal (2013) reported that 5000 villages are served by hybrid-renewable mini-grids only in the Sunderban Islands of the West Bengal in India. The Indian government set a target of 10,000 mini-grids delivering at least 500MW by 2020 (Bhushan and Kumarakandath, 2016). Zhang and Kumar (2011) focused on China's success in renewable mini-grid based electrification and reported 377 villages are served by small-hydro projects and 688 villages by PV and PV-wind mini-grids in Western China alone. Decentralized mini-grids using locally available single or more renewable resources can be a sustainable option to replace the traditional models (ARE, 2008 & 2012 and UNEP, 2016). Because of diurnal and seasonal limitations of renewable resources, application of diesel generator and battery backup in a hybrid combination has become a popular choice among the system designers and investors. Such a mini-grid system can be a complex combination of multiple renewable energy sources and variety of end users demand. Based on the rapid decline in the component price of small scale renewable power generating systems Levin and Thomas (2016) suggested that developing countries can leapfrog to decentralized renewable electricity service model to tackle the crisis of electricity.

The supply of electricity produced from solar PV, wind turbines, micro hydro or biomass resources, in suitable hybrid combinations including required batteries as storage and supplementary diesel generator(s) as back up, has been used in many countries of Asia and Africa (Palit and Chaurey, 2011 and ADB, 2014). Some micro/small-hydro mini-grids are in operation in Nepal, India, Sir Lanka and Vietnam. Such a distributed energy generation approach based on wind, solar and biomass has gained some success in India and Nepal. According to the World Bank (2012) despite having access to national grid many households and businesses in developing countries maintain diesel generators or battery backups to tackle the frequent and prolonged power outage. Following the example of other countries, government of Bangladesh is very keen on hybrid mini grid options as part of its power division master plan (Power Division, 2011:2).

Policy support is a prerequisite for off-grid electrification through hybrid mini-grids in developing countries. Martin and Susanto (2014) pointed that in Laos subsidy exceeds 70 percent for grid-based electrification whereas it is only 26 percent for the decentralized option. The same study highlighted that in rural Thailand households receive 50kWh of free electricity every month from the grid, which costs the government around USD 30 million; no such support or incentive is available for distributed mini-grid power generation. Although decentralized rural electrification initiatives are poorly integrated compared to the grid counterpart (Urpelainen, 2014) policy makers are getting more inclined to the potential of mini-grid based electrification strategies (Narula, et al., 2012).

Bangladesh introduced its complete national renewable energy policy in 2008, which emphasized support for mini-grid based rural electrification. The average number of households in rural Bangladesh is around 200 per village (BBS, 2012), which apparently can be suitable for micro grid operations (Palit and Chaurey, 2011). Bangladesh can follow the example of India where many densely populated remote areas are served by distributed renewable energy generating systems supplying electricity to households through local grids that have been considered as economically feasible options (Chaurey and Kandpal, 2010). However, very low load demand by households poses the real challenge to implement the business case for such mini-grids in Bangladesh.

Bhattacharyya and Palit (2016) suggested that cost-effective rural electrification towards universal electricity access by 2030 will remain a major challenge for many developing countries as lack of financing resources, weak governance and organizational inefficiencies hinder the initiatives. Many sources (Setiawan, et al., 2009; Belfkira, et al., 2009; Kumar, et al., 2009; Chen, et al., 2011; Dalwadi, et al., 2011; Viral, et al., 2013; Ulsrud, et al., 2011; Sadiqui, et al., 2011; Bekele and Tadesse, 2012 and TERI, 2010) highlighted the foreseeable limitations and possibilities associated with the hybrid mini-grids. However, the challenges in general are: complex local consumption (time varied load) pattern, uncertainties in seasonal demand, poor consumption per connection, expensive storage, lack of skilled manpower, distribution loss and power theft. On the other hand there are many benefits that can support the possibilities of mini-grid diffusion. These are reduced health hazards, better proposition than standalone SHS or diesel grid, regeneration of local economy and modular size to support future expansion if required. While, Martel, et al., (2012) and Nielsen and Fiedler (2012) highlighted the complex and uncertain load demand as the major issue, other researchers indicated financial uncertainties (Poulin, 2012; Leeuwen, 2013 and Lilienthal, 2013) and expensive storage and limited technical support (Léna, 2013 and Mahmud, 2012) as major challenges. Better quality electricity compared to other standalone systems and diesel grids (Shyu, 2012; Vallvé, et al., 2012 and Mahmud, 2012) with lower cost per unit (Léna, 2013; Gorn, 2010; Dekker, 2012 and Schmid and Hoffman, 2004) and helping local empowerment (Mahmud, 2012) reported as major opportunities. There have been only a few works related to hybrid mini-grid techno-economic feasibility studies (Nandi and Ghosh, 2009 & 2010; Mondal and Denich, 2010:1; Hasan, et al., 2011; Khan et al., 2012; Bhattacharyya, 2015) done in Bangladesh and the limitations and possibilities of this electrification approach are still to be explored.

Bangladesh had its first 10kW Wind-PV hybrid mini-grid systems installed on Saint Martin Island and the project was fully financed by UNDP and MEF (Ministry of Environment and Forest). The advantage of this hybrid combination in this location is, when there is intense sunlight, wind speed is low and vice-versa. Battery bank and diesel generator backs up the whole system. Power is converted to AC to be supplied to the end users through an underground cable line. Unfortunately this project is no longer in operation. The first 250kW rice-husk-burn biomass power plant of the country was set up at Kapasia, Gazipur by the 'Dreams Power' to supply electricity to the nearby areas at USD 0.16/kWh. This mini-grid attempted to supply electricity at the same price as the Rural Electricity Board (REB) offered for the consumers in other areas. The private investor Dreams Power invested 20% and 60% came from the World Bank as grant and the rest 20% was loan from IDCOL (Daily Star, 2008). This project has been out of business since 2013. There are a few more decentralized hybrid systems setups in different parts of the country, i.e. wind-PV system in Sandwip Island, wind-PV-diesel system in Kuakata. Performance data of these hybrid-renewable energy systems have not been available yet in any published literature or report. However, during a field visit in Bangladesh the up-to-date performance and status of some mini-grid projects were studied as a part of this research work and are later analyzed and presented in chapter-5 to suggest sustainable business models.

2.3 Potential renewable energy resources for decentralized mini-grids in Bangladesh

Solar, wind and biomass are the three main renewable energy resources identified as having the greatest potential for electricity generation in Bangladesh (Mondal and Denich, 2010:1; Mondal and Denich, 2010:2; MPEMR, 2015; Nandi and Ghosh, 2009; Rahman, et al, 2013 and Hossain and Badr, 2007). However, there is some potential for micro-hydro in the hilly areas i.e. Chittagong Hill Tracts. Apart from these the country has very limited hydro resources to produce electricity except from the famous Karnafuli River. The tidal resource potential off the coast of the Bay of the Bengal has not been studied yet. The World Bank (2015) reported 345MW of current installed capacity including the large hydroelectric plant (230MW) in Kaptai (Figure 2) and estimated the renewable energy potential of Bangladesh as 3,366MW (Table 2.1).

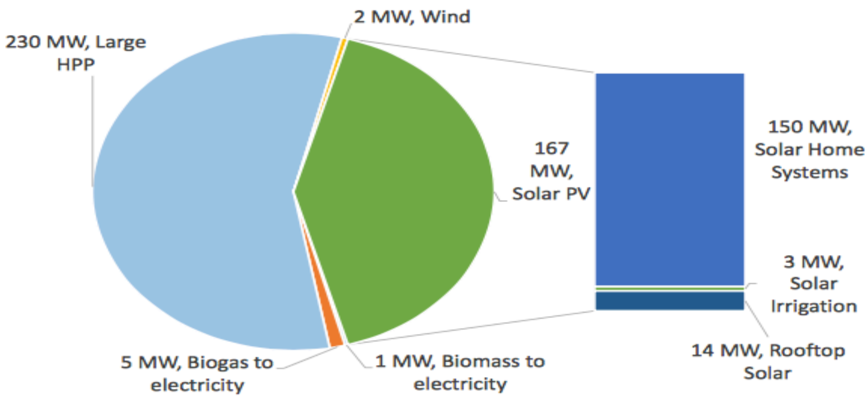


Figure 2: Installed RE capacity by resource type (World Bank, 2015)

Technology	Resource	Capacity (MW)	Annual Generation (GWh)
Solar Park	Solar	1400*	2000
Solar Rooftop	Solar	635	860
Solar Home Systems	Solar	100	115
Solar Irrigation	Solar	545	735
Wind Park	Wind	637**	1250
Biomass Generation	Rice Husk	275	1800
Biogas Generation	Animal Waste	10	40
Waste to Energy	Municipal Waste	1	6
Small Hydro	Hydropower	60	200
Mini-grid	Hybrid	3***	4
Total		3666	7010

*Excluding agricultural lands, ** Excluding flood-prone areas, *** Based on planned projects only (not a theoretical potential)

Table 2.1: Renewable energy potential in Bangladesh (Source: World Bank, 2015)

Only the SHSs have exceeded the expected potential in the off-grid areas of Bangladesh. Decentralized hybrid mini-grid based rural and remote area electrification still needs to go a long way.

2.4 Renewable resource assessment for hybrid mini-grids (Methodology and findings)

Bangladesh is characterized by the subtropical monsoon climate. Weather elements vary distinctly across three major seasons i.e., summer, monsoon and winter. While nominating the locally available renewable resource(s) for decentralized mini-grid based electricity generation, changes in seasonal availability need to be considered carefully. Literatures (Hossain and Badr, 2007 and Hossain, et al., 2017) reported seasonal variation in solar, wind and biomass resources. Salehin, et al., (2016) suggested a combination of renewable resource availability with the hybrid mini-grids for the optimum system performance. This study therefore suggested the renewable resource assessment for mini-grid application in Bangladesh.

Renewable energy potential for a specific area and for certain technology application is related to different factors. Norton (2011) proposed a comprehensive approach following some sequential stages (Figure 2.1) for renewable energy resource assessment for practical application. Izadyar et al., (2016) further adopted this assessment into a framework to access the actual renewable energy potential for a specific remote area. They described the potentials in different steps as theoretical potential, geographical potential, techno-economic potential and finally the market potential. Theoretical potential refers to the possible maximum capacity utilization of a certain renewable resource by applying the full range of technological knowhow supported by the required investment. On the other hand geographical and techno-economic potentials are directly related to the geographical suitability of an area to adopt a certain technology and the technological ability and affordability of a country respectively. Finally the market potential of a renewable resource for a country refers to the scale of ability of that country to harness the renewable resource in terms of its techno-economic ability and the geographical suitability. According to the framework suggested by Izadyar et al., (2016), the theoretical potential of a renewable resource may not always be applicable for power generation in off-grid mode due to the geographical and techno-economic factors associated. Therefore, the market potential is the actual potential that needs to be assessed to apply with off-grid applications. However, Bangladesh's off-grid electricity market has got techno-economic limitations (i.e., poor investment environment, lack of technological knowhow etc.) and geographical issues (i.e., severe seasonal flooding, frequent tornedos and typhoons, coastal surge etc.). Therefore, for the scope and the purpose of this study the theoretical potential of renewable resources of Bangladesh has been studied following the work of Mondal and Denich (2010).

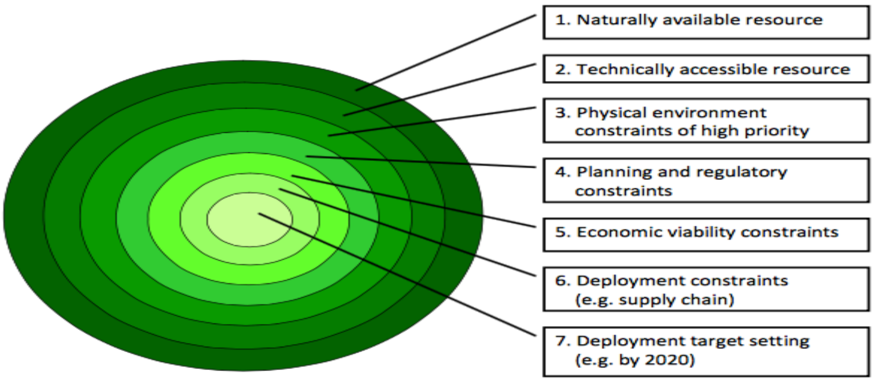


Figure 2.1: Renewable resources potential study sequence (Source: Norton, 2011)

To identify location specific renewable energy resources all the secondary published data and unpublished official data from different government and non-government organizations were collected for this study and a resource map has been developed later in this chapter (Fig. 2.8). The whole country can be divided into different regions depending on the availability of potential resources for hybrid mini-grid application *i.e.* Wind-Solar, Biomass-Solar, Small Hydro-Solar and wind, biomass, small hydro and Solar itself. This resource mapping will allow policy makers and investors to easily decide the type of energy mixes to be employed for a proposed mini-grid and which in turn enhances the possibility of replication and scaling up for the decentralized hybrid mini-grids.

2.4.1 Solar Resources

Available solar radiation data for Bangladesh were collected from the database of National Renewable Energy Research Centre (NREL[1, 2,3]), Renewable Energy Research Centre (RERC[1]) and German Aerospace Centre (DLR[1]). Simultaneously these data were compared to the United Nations Environment Program's (UNEP) SWERA[4] (Solar and Wind Energy Resource Assessment) data. However, no significant difference was observed. Therefore, NREL database was used to derive the estimated solar energy potential (P_E) for Bangladesh as a function of land area per solar class (where each solar class corresponds to a range of value represented by $kWh/m^2/day$; Table 2.2). A specific range of $0.5 kWh/m^2/day$ correlates to each solar class. Potential energy (P_E) was calculated for a year applying the 10% efficiency of conversion[3] using the following equation (Rahman, et al., 2013):

$$P_E = \text{Productive land x } kWh/m^2/day \text{ x } 0.10 \text{ conversion x } 365 \text{ day}$$

A high spatial resolution dataset of 1km to 40km cells was applied[3] in this case. Available measured or estimated NREL database between 1961 and 2008 has been applied as time series input for this purpose and estimated potential energy presented in table 2.2. The average potential solar energy resources calculated here (Table 2.2) for Bangladesh resemble the findings of Mondal and Denich, (2010) and Nandi et al., (2012).

Class	Capacity factor	$kWh/m^2/day$	TWh/y	
1	12.03096	<= 3.0	82	
2	15.52001	3.0 – 3.5	8,439	Average
3	17.91658	3.5 – 4.0	7,812	potential
4	21.29447	4.0 – 4.5	514,466	**137,419**
5	24.65504	4.5 – 5.0	247,210	Per year
6	29.20168	5.0 – 5.5	46,508	

Table 2.2: Estimated solar energy resources for Bangladesh (Source: calculated by author from the NREL[3] Database)

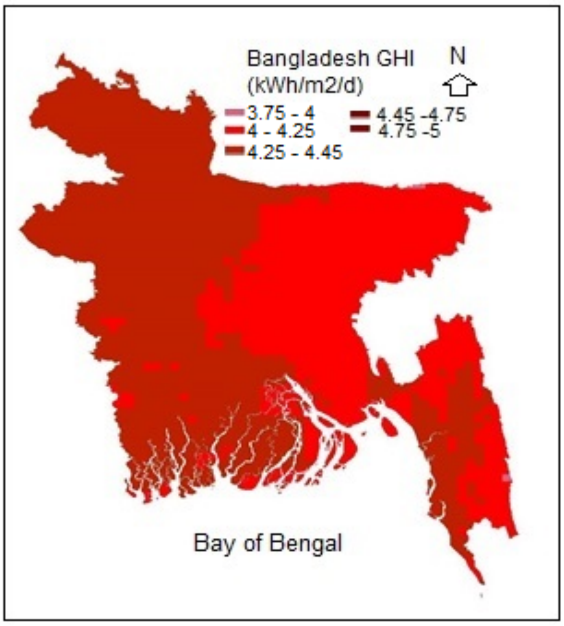


Figure 2. 2: Global Horizontal Irradiance map for Bangladesh (APCTT-UNESCAP[2])

Global Horizontal Irradiance (Figure 2.2) shows overall good potential of solar resources across the country while northwest and the southwest regions generally having higher intensities compared to the whole northeast, middle of the country and some parts of the southeast.

Hours/ Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					Average hourly Global Horizontal Irradiance (kWh/m2)							
5.30	-	-	1	5	17	19	11	7	3	-	-	-
6.30	3	8	29	66	106	93	86	66	58	46	31	11
7.30	57	93	148	198	252	200	198	180	165	169	157	97
8.30	175	254	318	354	406	321	355	288	303	324	331	237
9.30	300	424	489	521	561	416	438	433	435	473	490	382
10.30	411	573	629	666	681	494	503	514	485	487	580	479
11.30	494	672	712	751	727	532	548	537	485	520	614	498
12.30	518	701	722	764	711	543	570	535	486	488	573	489
13.30	483	646	657	693	641	500	503	482	441	406	510	426
14.30	379	528	541	553	577	451	463	453	385	323	377	309
15.30	236	353	377	402	419	329	372	356	281	208	204	183
16.30	94	175	204	237	257	215	244	231	164	76	57	54
17.30	10	37	55	72	93	93	107	89	45	6	1	2
18.30	-	-	2	4	11	17	18	8	1	-	-	-
Average kWh/m2/d	3.16	4.46	4.88	5.28	5.46	4.22	4.42	4.18	3.74	3.53	3.92	3.17

Table 2.3: Monthly average hourly Global Horizontal Irradiance (Source: NREL[3])

In general the country has good diurnal Global Horizontal Irradiance (GHI) from 7.30 in the morning to 4.30 in the afternoon (Table 2.3). A little variation is observed between the winter and summer months.

Based on the solar energy resources (Figure 2.2 & 2.3 and Table 2.2 & 2.3) over the country it can be said that most of the solar energy extracting systems can be used for power generation in Bangladesh. Bhuiyan (2013) reported the average monthly global solar radiation in Bangladesh as 4.255kWk/m^2/d and solar radiation diffuse component is approximately 50%. This report compared the GHI data based on the satellite image, theoretical modeling and measured data and concluded that any non-concentrating PV technology should be suitable for energy generation in Bangladesh.

2.4.2 Wind Resources

Bangladesh has very limited official wind study data. BMD (Bangladesh Meteorological Department) has been collecting wind data since the independence of the country in 1971. All the BDM weather stations across the country collect only surface wind data measured at 5m to 10m heights. These analogue data are not suitable for wind energy assessment. During last few years some government, non-government and donor organizations have been engaged in wind resource assessment activities at different locations of the country. LGED (Local Government Engineering Department), REB (Rural Electrification Board), BCSIR (Bangladesh Council of

Scientific and Industrial Research), BAERC (Bangladesh Atomic Energy Research Commission), BUET (Bangladesh University of Engineering and Technology), BCAS (Bangladesh Centre for Advanced Studies), SWERA (Solar and Wind Energy Resource Assessment) and WERM (Wind Energy Resource Mapping) are the major bodies actively working in this field. However, no conclusive wind resource data for Bangladesh has been yet published.

The first complete wind resource mapping was proposed by Khan, et al., (2004) and this map presented wind data at 30m height (Figure 2.3). According to this database, for wind energy use the areas are limited mostly in the coastal regions. Cox’s Bazar, Teknaf, some coastal belt of Chittagong, Saint Martin Island, Kutubdia, Moheskhali, lower parts of Barisal, Bhola, Bagherhat, Noakhali and other islands like Hatia and Swandip etc., would be good locations for wind energy extraction. There is a little potential of wind energy resources at a very high altitude in the north of the country. The south and southwesterly wind blows over Bangladesh from March to September with monthly average speed of 3m/s to 6m/s (Ahmed, 2002) that makes the islands along the coastline suitable for wind power generation.

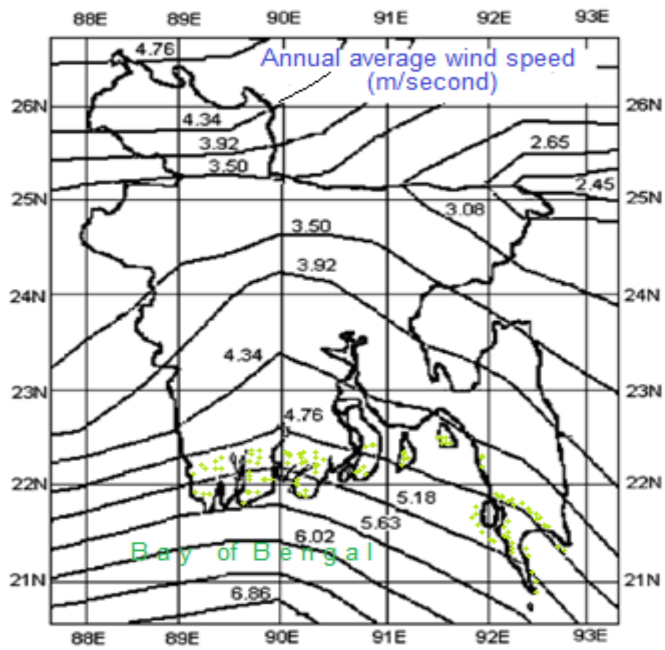


Figure 2.3: Wind map of Bangladesh at 30m elevations; green dotted areas showing potential wing energy areas (Source: modified from Khan, et al., 2004)

For the purpose of this study to create the renewable resource mapping and wind energy generation through hybrid mini-grids the available data were compared to the APCTT-UNESCAP[2]) database, which offers wind data at 50m height. However the most up-to-date wind energy database of WindNavigator[5] (version 4.9.6) was also consulted to input the time series data for the hybrid power generating system design.

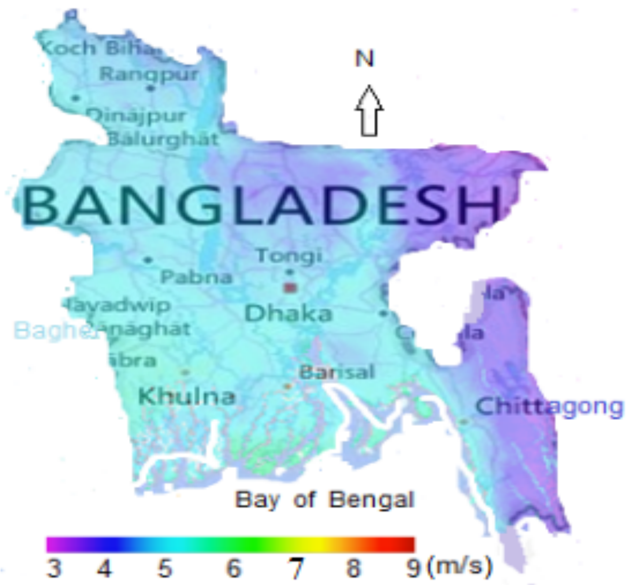


Figure 2.4: Wind resource map of at 80m heights Bangladesh generated by WindNavigator[5]

Wind data analyzed from the WindNavigator[5] database showed great resemblance with the recent study of Mukut, et al., (2008) for the wind energy potential at some coastal regions of Bangladesh.

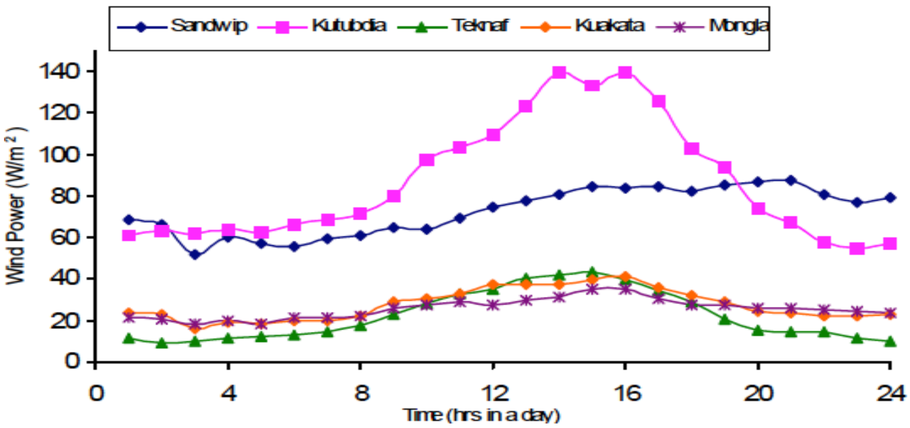


Figure 2.5: Wind power potential in different coastal regions of Bangladesh (Mukut, et al., 2008)

Most of the southern parts of the country represent the potential wind power prospects (Figure 2.4 & 2.5). Sandwip, Kutubdia and Teknaf are at the forefront of wind energy potential (Figure 2.5) with the highest diurnal value in the midday and early evening (12 noon to 8pm). However, there are some wind energy potentials observed in the north and northwest of the country (Figure 2.4).

2.4.3 Biomass resources

Most of the agricultural biomass resources available in Bangladesh represent lower energy conversion (density) compared to fossil fuels. Such resources tend to have high unit cost of energy because of added handling, storage and transportation costs. On the other hand some seasonal biomass especially the crop residues are geographically too dispersed to consider as economically viable as they involve high collection and transport costs. To avoid the long distance transportation and handling costs biomass need to be sourced locally where it can be collected in bulk, i.e., husk from rice mills. To ensure available supply of seasonal biomass throughout the year mini-grid projects need to build the required stock during the peak season of that particular resource.

Like other energy sources bio-power has some potential environmental risks, which need to be addressed carefully. Beneficial biomass resources need to be identified and managed with proper sustainable policy implementation. Based on the secondary data paddy has been taken as the major source of biomass considering rice husk to be used as the fuel for power generation by the proposed mini-grids in this study.

Bangladesh produces around 40-45 million metric tons (MT) of paddies annually (USDA, 2015). Most of the production comes from the north of the country (Figure 2.6). Kumar, et al., (2013) reported availability of 8-9 million MT of rice husk every year considering husk yield as 20% from the paddy. Abedin and Das (2014) estimated a 400MW of electricity generation capacity from the rice husk in Bangladesh using the BGT (Biomass Gasifier Technique). This estimate is based on the assumption that half of the husk is used for other purposes, i.e., household cooking in rural areas, steam generation for rice parboiling etc. However, availability of the resource, technology type and operational efficiency are the main factors that determine the amount of electricity that could be produced from husk.

The major verities of rice production across the country and other biomass sources (tea, jute, common forest) have been shown in figure 2.6. Only rice husk is considered in this research for power generation as other biomass resources have lower energy potential and are mostly used as domestic cooking fuel.

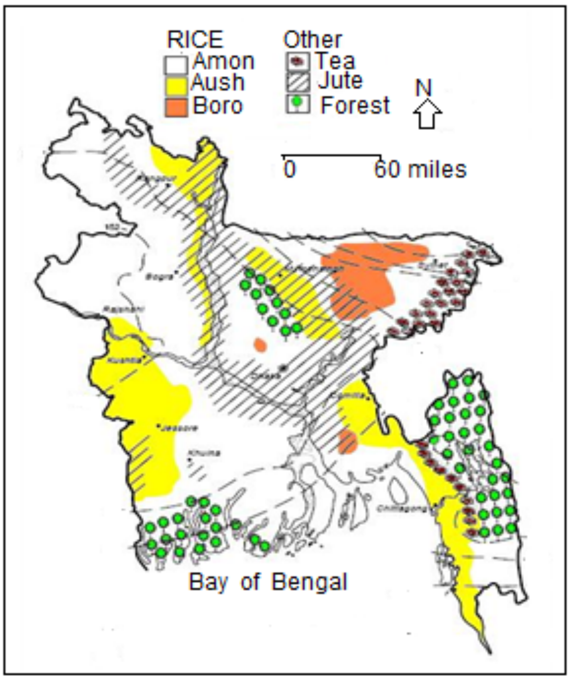


Figure 2.6: Major biomass resources distribution (Source: APCTT-UNESCAP[2] and BADB[6])

2.4.4 Small Hydro resources

Bangladesh has been identified with very limited hydropower resources. Micro hydro resources across the country are yet to be explored. JAICA[7] (Fig. 2.7) recently identified few suitable micro-hydro locations in Chittagong Hill Tracts and Stream Tech (US based consulting firm) advised locations along the Bakkhali, Matamuhuri and Sangu rivers. None of the studies assessed the actual potential for power generation. Frequent flooding in low-lying terrains is the major hindrance in implementing any micro hydropower generation projects in Bangladesh.

The first micro hydro power plant was installed by LGED in Bamerchara, Bashkhali upazella in Chittagong district. This 10kW unit with cross flow turbine only generated 4kW electricity due to insufficient water head (Chowdhury, et al., 2012). Another

10kW micro hydro plant has been serving 140 families in Bandarban district using the flow of a hilly stream.

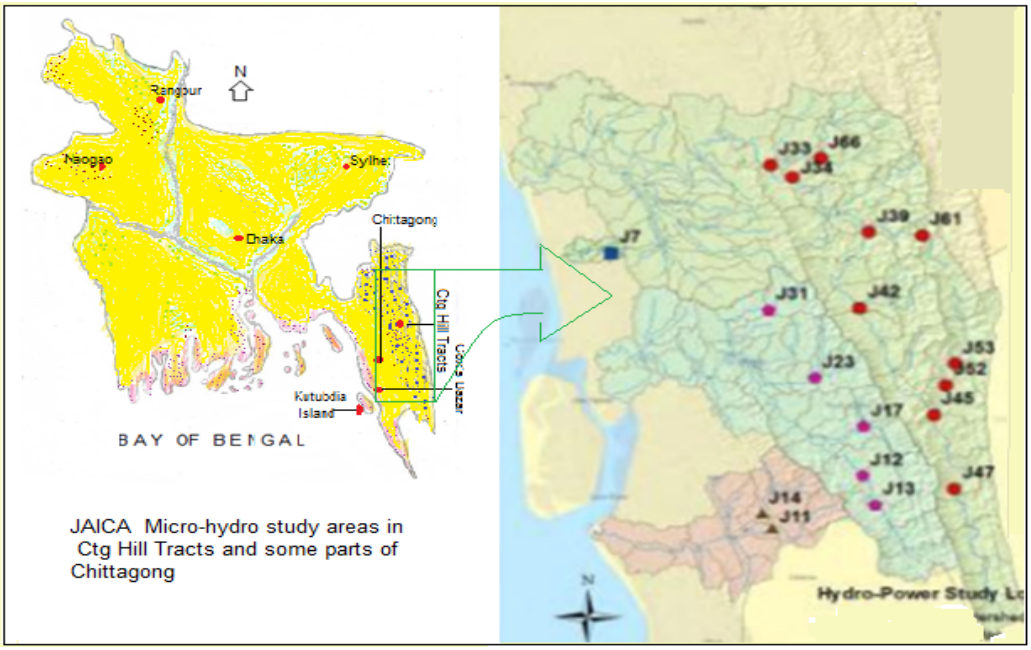


Figure 2.7: Micro hydro study areas carried out by JAICA[7] in Chittagong Hill Tracts and some parts of Chittagong

Some potential micro-hydro sites have been identified by different agencies (LGED, SPARSO[8]) in the recent years. While identifying the site potential theoretical power output (P_T) is defined by estimating the water head and flow rate, and this can be expressed as the equation below:

$$P_T = f \times H \times g$$

Where, P_T = potential of hydro power (kW)
f = available rate of water flow (m^3/s)
H = gross water head in (m)
g = constant of gravity ($9.81 m/s^2$)

BPDB[9] identified some potential sites for micro hydro plants across the country (Table 2.4). Moreover, LGED[10] (Local Government Engineering Department) identified few more sites in Chittagong Hill Tracts (Table 2.5).

District	Site location	Generation potential (kW)
Chittagong	Foy's Lake	4
	Choto Kumira	15
	Hinguli Chara	12
Chittagong Hill tracts	Sealock Khal	81

	Lungi Chara	10
	Budia Chara	10
Sylhet	Nikhari Chara	26
	Rangapani Gang	616
	Madhab Kunda	78
Jamalpur	Bhugai-Kongsa	69 for 10 months 48 for 2 months
	Marisi	35 for 10 months 20 for 2 months
Dinajpur	Dhauk	24
	Chawai	32
	Talam	24
	Pathraj	32
	Tangan	48
Rangpur	Bhurikhora	32
	Fulkumar	48

Table 2.4: Potential micro hydro sites identified by BPDB[9]

District	Site location	Power potential (kW)
Bandarban	Sealock Khal	30
	Taracha Khal	20
	Rangachari Khal	10
Khagrachari	Nunchari Khal	5
Rangamati	Hnara Khal (Kamal Chari)	10
	Hnara Khal (Kure Mukh)	30

Table 2.5: Potential micro hydro sites identified by LGED[10]

Mahmud et al., (2012) identified some potential micro-hydro sites and estimated power production potential (Table 2.6).

District	Site location	Power potential (kW)
Chittagong	Mohamaya Chora	4.95
	Choto Kumira Canal	19.19
	Rungchori Canal	37.81
Bandarban	Sailopropat Spring	42.74

Table 2.6: Potential micro hydro sites identified by Mahmud, et al., (2012)

Some of the sites identified by BPDB are in seasonal flood plains and project realization could be risky. Most of the sites identified by both BPDB and LGED are located under the national grid jurisdiction. Therefore, possibilities of implementing distributed mini-grid electricity generation in such areas are very thin.

As numerous rivers crisscross Bangladesh, electricity generation using the kinetic energy of river flow could be a major source of off-grid electrification. Study (Islam, et al., 2013) suggests that applying small-scale hydropower technology electricity can be produced from the run of river water of many large and small rivers while highlighting the prospect of Gumoti and Surma River. Extensive research work is required to explore the suitable sites, their actual potential for micro-hydro power generation and associated risks.

2.4.5 Resource Map

Based on the above data a general resource map has been developed (Fig. 2.8) representing wind, solar, biomass and micro-hydro potential for mini-grid application purpose. It is clear from the map developed that solar resource is available all over the country, while wind is limited to most of the coastal regions and some northern part of the country. Biomass (rice husk) is concentrated only in some part of the country. Notably, rice is a common crop in Bangladesh and produced all across the country. However, as a potential resource this research only taken the highly production intensive areas into account. Micro-hydro potential is very much restricted to Chittagong Hill Tracts and along some riverbanks of Chittagong. Nonetheless, more research and combination of findings by different agencies are required for a full pledged renewable resource mapping of Bangladesh.

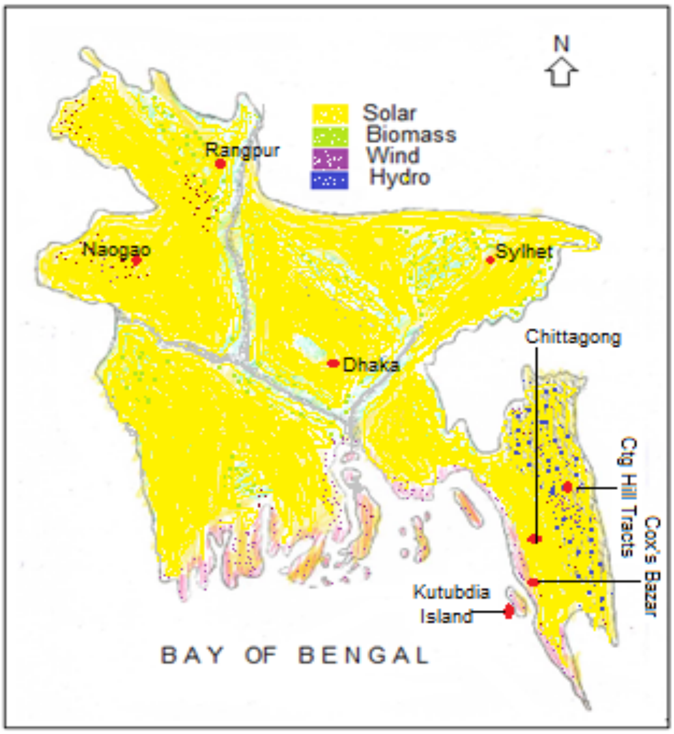


Figure 2.8: Potential renewable energy resources map

2.5 Topographical Challenges in Mini-grid Implementation

Seasonal floods regularly affect Bangladesh, the low-lying delta of the Ganges, Brahmaputra and Meghna Rivers. Major parts of the country are identified with prolonged flood, flash flood and serious riverbank erosion (Figure 2.9).

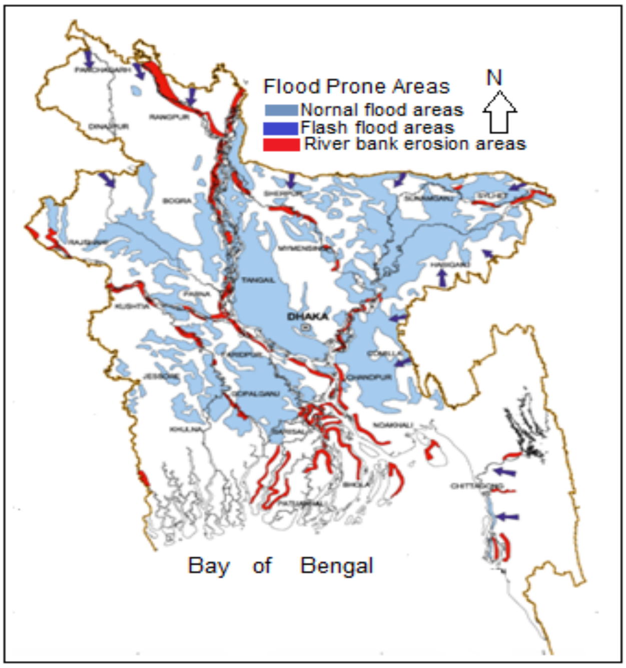


Figure 2.9: Flood prone areas of Bangladesh (Litchfield, 2010)

Due to the dispersed habitation in the rough and hilly terrain of Chittagong Hill Tracts and other hilly regions national grid is literally unavailable in these areas. The river valleys, especially the Karnafully River (and its tributaries) and hilly ranges are characterized by various elevations. Some of these are Basitaung (664m), Tinda (898m), Keokradong (884m), Waibung (808m), Rang Trang (958), Mowdok Trang (905m) and Mowdok Mual (1003m) etc. Despite the abundance of one or more renewable resources the design, installation and maintenance of commercially viable mini-grid systems in such areas could be a real challenge.

2.6 Hybrid Mini-grid: system Details

Hybrid mini-grids can be of different combinations based on the renewable resources (Table 2.7) and may contain some unique features (Figure 2.10). Regardless of the resource and technology combination a hybrid system contains three main subsystems and these are:

- Production
- Distribution and
- Demand

Depending on the type and nature (resource and technology combination, load requirement and management strategy) of the mini-grid a subsystem may require different technical setups.

Production: This part of a hybrid system is designed based on its projected generation capacity. Selection of technology is determined by carefully considering the resource availability and component cost analysis. The key components of this subsystem are:

- Renewable Energy producing component (PV, wind, biomass, hydro)
- Converters (inverter / rectifier)
- Power storage (battery)
- Power backup (diesel generator)
- Bus bar (interconnecting the components)

Production subsystem may include more technology combinations i.e., RE share management system, battery charge management system.

Distribution: This part of a hybrid system consists of several components to transmit and deliver the produced electricity to the end users through a local grid. Distribution system can be of either a single phase or a three-phase grid supplying AC or DC. Decision about this is made by the project designer and owner depending on the electrical appliances to be used by the local consumers. Project cost and maintenance vary with the relative choice. However, the type of grid cabling (over ground or underground) needs to be selected considering the safety features and costs.

Demand: This part of the hybrid system is generally built in line with its own application strategy and customer demand characteristics. An efficient demand management strategy balances the supply and consumption. This subsystem includes customer meters, all external and internal cabling and all the appliances consuming electricity from the system.

However a smart control system can offer the mini-grid much better performance by using the optimal integration among the system components. An intelligent dispatch controller (IDC) can be used in a mini-grid to achieve maximum satisfaction of the end users. IDCs perform timely required system controls and make critical decisions by responding to variable demands through adding or removing integration of multiple distributed energy resources (DER) without affecting the stability of the grid.

Solar-Wind Battery+/Genset	Solar Battery+/Genset	Wind Battery+/Genset
Small Hydro Battery+/Genset	Solar-Small Hydro Battery+/Genset	Wind-Small Hydro Battery+/Genset
Biomass Battery+/Genset	Solar-Biomass Battery+/Genset	Wind-Biomass Battery+/Genset

Table 2.7: Possible hybrid combinations for mini-grid in Bangladesh

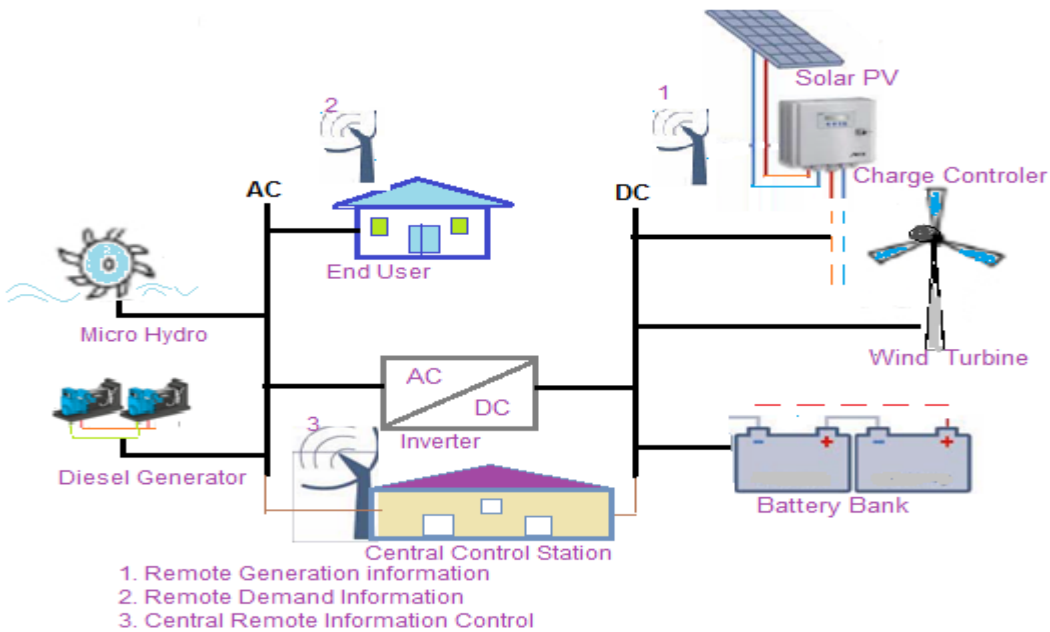


Figure 2.10: Schematic of a hybrid mini-grid with smart control (Source: Author)

2.7 Conclusions

Studies and literature reviews carried out in the previous chapter and earlier in this chapter regarding rural electrification status in Bangladesh, global trend in small scale renewable energy generation and renewable resource availability in Bangladesh indicate a clear demand of off-grid electricity generation using distributed mini-grids. However, various sources (Ahmed, et al., 2012; Knuckles, 2016; Sen, et al., 2016 and Yadoo and Cruickshank, 2012) pointed the different challenges i.e., financing, resourced based optimum system design, socio-economic criteria, willingness to pay or affordability and critical supply and demand management. The following chapters (Chapter 3-5) of this thesis have systematically addressed all the opportunities and challenges and recommended the best practice in this context (Chapter 6).

Notes:

1. Global Horizontal Irradiance map of Renewable Energy Research Centre (RERC), National Renewable Energy Laboratory (NREL), German Aerospace Center (DLR) showing averaged NREL and DLR maps tuned to Dhaka (Links: http://www.nrel.gov/gis/solar.html ; http://en.openei.org/datasets/files/965/pub/swera_bangladesh_fullreport.pdf ; http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/publications/SWERA_10km_solar_finalreport_by_DLR.pdf)

2. APCTT-UNESCAP: Asian and Pacific Centre for Transfer of Technology Of the United Nations – Economic and Social Commission for Asia and the Pacific (ESCAP); Bangladesh Renewable Energy Report; Energy Research Centre, University of Dhaka.

3. NREL (National Renewable Energy Laboratory), USA database can be accessed from https://nsrdb.nrel.gov/download-instructions (or https://catalog.data.gov/dataset/solar-monthly-global-horizontal-ghi-gis-data-at-40km-resolution-for-bangladesh-from-nrel-ed8d0/resource/8272fea1-6d46-43e0-b642-13c6ac64fbd8

4. United Nations Environment Program's (UNEP) Solar and Wind Energy Resource Assessment (SWERA) (can be assessed from http://en.openei.org/datasets/dataset/30d09781-7d0c-4aad-a18f-0e9d84dda2f6/resource/cb3b69e6-927e-45d6-aa53-3c7a0575b3f4/download/swerabangladeshfullreport.pdf)

5. WindNavigator, AWSTruepower, Global Wind Resource Database (subscription required), Albany, New York, USA (accessed at https://windnavigator.com)

6. BADB: Bangladesh Agricultural Development Board, Ministry of Agriculture, Krishi Bhaban 49-51, Dilkusha Commercial Area Dhaka-1000.

7. JAICA: Japan International Cooperation Agency.

8. SPARRSO: Space Research and Remote Sensing Organization, Agargaon, Dhaka 1207; (http://www.sparrso.gov.bd/new/)

9. BPDB: Bangladesh Power Development Board, Government of Bangladesh, (http://www.bpdb.gov.bd/bpdb/index.php?option=com_content&view=article&id=26&Itemid=24)

10. LGED: Local Government and Engineering Department, Government of Bangladesh

Chapter 3

Market analysis

Chapter Highlights

This chapter investigates the characteristics of the rural consumer market at the bottom of the economic pyramid in Bangladesh. It presents the existing energy situation, actual rural household energy demand, willingness to have electricity from proposed mini-grids, ability to pay and willingness to pay through an extensive field survey. This type of work is unique and is done for the first time in Bangladesh. The findings of this field study help to make informed data input for the mini-grid design and analysis in the subsequent chapters.

*C*hapter 3

3 Market analysis

Analysis of the rural market for decentralized mini-grid electrification in Bangladesh

3.1 Introduction

A standard mobile phone handset used to cost around USD 1,000 and a single outgoing call USD 0.32 in the early days of cell phone technology launch in Bangladesh during 1996-97 (BTRC, 2015:1). In the course of 20 years a standard smart phone can be bought here now for only around USD 32 and a call can be made for as little as USD 0.0026. This mobile phone revolution has occured in Bangladesh through private investment (Mahbubani, 2008). As of January 2015, the country had approximately 121.68 million mobile phone subscribers (BTRC, 2015:2). Sullivan (2007) stated that adding one mobile phone customer would generate USD 6,000 to national GDP. Despite the mass diffusion of appropriate technologies and private investments in the mobile phone sector the country did not experience a similar development in the power sector and the prevailing poor rural electrification status remains a vital subject of research.

It has been pointed out in the earlier chapters that decentralised hybrid mini-grids have received very limited attention and thus no remarkable success in the electricity sector in Bangladesh. Despite several government and private initiatives the diffusion of this technology remains poor and therefore, investment opportunities are still unexplored. Success and failure of such projects in Bangladesh and other developing nations raised concern about the characteristics of the market at the bottom of the economic pyramid and confirms the importance of detailed market studies. Such studies have not been carried out so far in Bangladesh and are very limited in other developing countries as well. Therefore, this part of the research attempted to explore the rural market and consumer characteristics by answering the following questions:

1. What are the energy usage patterns among different socio economic groups?
2. Are the villagers willing to switch to mini-grid?
3. What will be the expected household load demand?
4. How much are the villagers willing to pay for proposed electricity?

3.2 Literature review

Researchers expressed their concerns in different papers (Rahman, et al., 2013; Paul, 2011; ARE, 2008; Barnes, 2007 and Ziaur, 2012) regarding the challenges of rural electrification related to institutional setup, financing and policy frameworks attributed to different geographical, economic and socio-political characteristics. Bangladesh is a unique example of these cases. The much-appreciated Rural Electrification Program (REP) of Bangladesh initiated in 1980 gained huge attention among many other developing countries as being very successful (Taniguchi and Kaneko, 2009). Despite REP's initial success the program has been facing many hurdles since 2006, which contributed to a remarkable decline in its growth (Rahman, et al., 2013). In 2008 the Bangladesh government finalized the national Renewable Energy Policy (Power Division, 2008) considering the limited indigenous fossil fuel resources with special emphasis on rural electrification. The vision of the strategic shift from grid extension to distributed generation by using renewable energy sources in non-electrified rural areas is yet to see any major success.

The exploratory work of Rahman, et al., 2013 identified the challenges and reasons for failure of rural electrification through conventional grid extension in Bangladesh. These are lack of investment, bad terrain, poor operation and maintenance, low number of connections per unit of extended grid and finally very low load demand per connection. Palit, et al. (2016) noted almost the same issues related to grid extension for rural electricity access in other South Asian nations. Household energy requirements are directly related to geographic, demographic and other socio-economic characteristics (Rao and Reddy, 2007; Miah, et al., 2010; Miah, et al., 2011). As rural electrification has the challenges of low number of connections, poor load requirements and financial constraints along with many socio-cultural factors; the market specific demand and characteristics need to be assessed carefully. This should include the study of consumers' demography, current status of energy usages, load demand, their affordability, willingness to connect and finally their willingness to pay for the electricity.

Urmee and Harries (2011) pointed out that increasing demand of electricity in Bangladesh is the result of socio-economic growth. On the other hand Rahman and Ahmad (2013) argued that increased energy access is a necessary vehicle for rural development. This rural development can be either the very initial or further development stage to improve the quality of life. 58% of rural households are energy poor and heavily dependent on kerosene for lighting purpose in Bangladesh (Barnes, et al., 2011). Mills (2003) reported that kerosene lantern's or lamp's measured energy consumption is around 53 litres per year for the simple wick types for an average of 3.5 hours a day operation. According to Iorkyaa et al. (2012) conventional kerosene lamps provide light output as low as 0.3 lumen per watt, which is very poor in comparison to standard LED light bulbs. Moreover, the health hazards and associated other risks of kerosene fuel use for lighting purposes are well documented in many literatures (Chamania, et al. 2015; Gad and Pham, 2014; Pattle and Cillumbine, 1956; American Cancer Society, 2006; Mashreky, et al. 2008; Asuquo, et al. 2008 and Oludiram and Umebese, 2009) around the world. Mills (2013 & 2016) reported house fires, kerosene burns and contaminated indoor air quality associated with kerosene lighting in Bangladesh. The later (Mills, 2016) report highlighted that infants in Bangladesh incur about 40% of the fuel based lighting burns. Mashreky et al., (2008) specified that fuel based lighting cause 17,000 childhood burn injuries in Bangladesh.

Pode (2013) concluded that improved lifestyle is the major factor for customer switching from kerosene to SHS. Komatsu, et al. (2013) reported that around 50% of households in rural Bangladesh continue to use kerosene at a monthly amount of 0.92L reduced from 3.932L for lighting purpose only even after installing SHSs. The main reasons behind households using kerosene for lighting purpose alongside the installed SHSs are inadequate load assessment and load management, insufficient energy storage, poor performance of the energy generating system, lack of proper service and maintenance and finally under size system due to less affordability (Asaduzzaman, et al., 2013). In Bangladesh 57.7% of the SHS users experience frequent unavoidable repair of batteries for an average cost of Tk. 228.41 per repair (Komatsu, et al. 2013). This phenomenon negatively affected the users satisfaction with their installed SHSs.

Moving from liquid fuel based lighting to other available means of electricity is just not a simple choice but a matter of financial affordability. Miah, et al. (2011) reported mean expenditure for energy usages in rural areas of Noakhali in Bangladesh to be USD 5.34 per month with a monthly mean income of USD 209.84, which is considered as a representative figure for other non-electrified areas of the country. Considering the price of kerosene Tk. 65 (USD 0.833) per litre (BPC, 2015), rural households energy expenditure remains the same or even less if electricity can be supplied at the standard rate of BREB through grid extension. In case of electricity to be supplied by decentralized mini-grids using renewable sources, customer affordability needs to be assessed, as unit cost of electricity would be higher in this case. Barnes and Foley (2004) identified the connection fees as one of the main barriers for the expansion of rural electrification and recommended to spread these costs over a longer period to be included in monthly electricity bills. Polli Biduyt Samiti's (PBS) connection fee and security deposit for a family of five is Tk. 1000 (USD 12.82) and is payable in advance (PBS, 2015).

Rural households pay higher unit cost for electricity generated from the SHSs in Bangladesh. The reason behind paying more in this case is not related to customer awareness and willingness toward renewable energy sources like the developed nations but this is the only available option for rural electrification in the market. Consumers in the USA are willing to pay more for generic green energy (Borchers, et al., 2007). However, the nature of the rural Bangladesh's electricity market is different from that of the USA. Akhi and Islam (2014) reported the unit cost of electricity from SHS as TK 85.98/kW (USD 1.10 /kWh) in Gazipur, Bangladesh. If better quality energy can be supplied at a competitive price compared to SHSs, rural customers would be willing to join electricity supply from mini-grids. Gaudchau, et al., (2013) emphasized on the customer's willingness to pay to support such a tariff for the electricity from the mini-grid, which can make the system economically viable. Kimera, et al., (2012) reported changes in generation cost of electricity due to variation in supply and demand of energy from mini-grids and suggested a time varying pricing approach for sustainable operation of the systems. Customers' need and variation in diurnal and seasonal demand of electricity should precisely be studied to set the sound operation and management of the mini-grid.

Energy consumption pattern and expenditure on energy usage in rural Bangladesh are different from developed economies. According to the office for national statistics (2014) on average, in 2012 British families spent around 5.1% of their income for energy usages, which was only 3.3% in 2002. Whereas a rural household with TK 10,000 (USD128) or more monthly income usually consume 54kWh/month electricity in Bangladesh and spend around 5 to 10% of their income on energy (Foysal, et al. 2012). Comparative expenditure on energy (considering electricity only) is higher in Bangladesh than many other countries. In general energy expenditure here is primarily dependent on household's income and as the income varies with seasons, so does the energy consumption. In rural Bangladesh during the seasonal famine earning drops by 50-60%, which results in a decrease in expenditure on food by 10-25% (Mobarak, et al. 2011). Energy consumption is affected as well due to seasonal reduction in income. However, energy consumption does not change considerably with a little increase in income level (Hassan, 2014). With increasing GDP growth, rural energy demand would shift to more electricity intensive usages in Bangladesh (Debnath, et al. 2015). While studying renewable mini-grids for off-grid areas in Bangladesh, researchers (Bhattacharyya, 2015; Hasan, et al., 2011 and Groh, et al., 2015) applied only theoretical load profiles. For optimum demand and generation management of a mini-grid it is important to know the actual load demand along with diurnal and seasonal variations.

Energy poverty[1] (58%) is higher than income poverty (45%) in rural Bangladesh where access to modern energy infrastructure is very limited (Groh, et al. 2016) and realistically people here have low level of knowledge regarding possibilities and benefits of renewable energy (electricity) supply (Hassan, et al. 2014). Households would pay more for electricity supplied from renewable mini-grids than kerosene but eventually the unit cost of lighting, as cost per lumen-hour from such distributed generations will be much cheaper than lighting by kerosene.

Different studies reported ranges of electricity prices from renewable mini-grids across developing countries. Azimoh, et al., (2016) presented the levelized cost of electricity (LCOE) ranging between USD 0.08 to 0.41/kWh for rural South Africa, whereas, Kolhe, et al., (2015) reported cost of electricity as USD 0.30/kWh for a mini-grid in Sri Lanka. Incase of Bangladesh Bhattacharyya (2015) found the LCOE varying from USD 0.465/kWh to USD 0.363/kWh while serving basic load and unconstrained load respectively. All of these studies indicated that LCOE from the renewable mini-grids are much higher than the costs of grid based electricity. ARE (2012 & 2013) emphasized the 'willingness to pay' of the customers as a major factor for the commercial success of the hybrid mini-grids. Sundt and Rehdanz (2015) applied meta-analysis on the existing literatures on households' willingness to pay in the developed economies and showed a general tendency of switching from conventional source of energy supply to renewable options. However, few studies reported customer willingness to pay for electricity from renewable sources in the developing countries. Abdullah and Jeanty (2011) reported that the rural customers in Kenya are willing to spent around 5% of their monthly income for the electricity supplied by solar PV. Twerefou (2014) studied consumer willingness to pay for improved electricity from renewable sources. Most of these studies focused on customers who already have means of electricity supply. However, there are a very limited number of studies (Abdullah and Jeanty, 2011 and Voisenat-Garces and Mukherjee, 2016) that investigated the customers' willingness to pay for electricity from renewable energy projects. Thus poor communities having no access to electricity are left excluded from such studies to identify their willingness to pay for the electricity from the renewable mini-grids. Therefore, this part of the thesis claims novelty in carrying out rural customers' willingness to pay for electricity from decentralized hybrid mini-grids along with the study of actual load profile and related factors in Bangladesh.

3.3 Methodology

Questionnaire based face-to-face interview is the most widely used technique in quantitative field data collection. For the consumers' electricity load assessment and willingness to pay (WTP) study many researchers have used this technique. Blennow (2004) and Hartvigsson, et al., (2015) followed face to face survey method for rural electricity load assessment in Tanzania and China respectively. Arega and Tadesee (2017) studied households' willingness to pay for electricity from renewable sources in urban and pre-urban areas of Ethiopia and collected the consumer data through face-to-face questionnaire based field survey. The same approach was applied by other researchers (Abdullah and Jeanty, 2011; Twerefou, 2014; Adaman, et al., 2014 and Gou, et al., 2014). To analyse the rural off-grid market in Bangladesh regarding their energy usages pattern, satisfaction with current means of lighting, expected electricity load demand and their willingness to pay for mini-grid based electricity; this study followed the face-to-face data collection method. Collected data were further analysed applying different techniques, which are elaborated below.

A door to door household survey was conducted to collect respondent data in December 2015 from six off-grid villages under three different administrative districts (Figure 3.1). Two adjacent /nearby non-electrified villages were selected from each district. These are *Loharchara* and *Porir dip* in Cox's Bazar, *Pakuria* and *Ichharkandi* in Gazipur and *Betagi* and *Rasulpur* in Feni, which were termed as V1, V2 and V3 accordingly as the study segments. 100 households were randomly selected for interview from each segment. To explore the probable load demand by irrigation activities, local business and other entities (school etc.) a total of 20 individuals were identified from each segment as well. Finally, a total of 360 face-to-face interviews using the carefully designed survey questionnaire (appendix I) from all three districts were performed with a staggering 100% response rate to all questions.

3.3.1 Study Areas

Detailed village level socio-economic data are not available officially in Bangladesh; therefore upazilla (A sub-unit of a district and a smaller geographical region in Bangladesh used for administrative purposes) or union (a geographical sub-unit of upazilla) level data were used to describe the selected interview areas. Generally per capita income, seasonal income variations and socio-economic conditions of a specific village in Bangladesh are reflected by the characteristics of the upazilla or union it belongs to (Khandker, 2012).

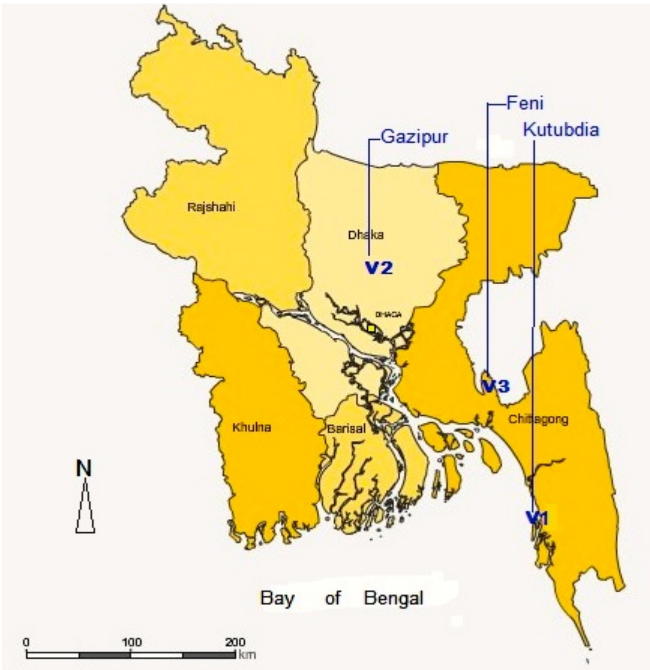


Figure 3.1: Map showing the study areas

Study segment V1 comprising of two nearby villages, *Loharchara* and *Porir dip* under the Kutubdia upazila in Cox's Bazar district represents the whole Island. Kutubdia is situated between 20°43′ and 21°50′ north latitude and between 91°50′ and 92°23′ east longitude. Secondary data regarding this study area was collected from BBS (2011). The island has a total of 55 villages without any formal grid connectivity. A local grid from the wind turbines and a couple of diesel grids are the main source of electricity for some villages. The economy of the island is dominated by agriculture. However, marine fishing and dry fish production are the unique characteristics of the most of the villages. The average household size is 5.5 and the literacy rate is around 34%. Island's male-female sex ratio is 111 with majority of the women are not associated in economic activities.

Study segment V2 is in Gazipur district previously being a sub division of Dhaka district consisting 1114 villages of different sizes (BBS, 2014). It lies between 23°53′

and 24°21′ north latitude and between 90°09′ and 92°39′ east longitude. The two sample villages *Pakuria* and *Ichharkandi* are in Gaccha union. Male-female sex ratio here is 106, average household size is 4 and literacy rate is 48%. Agricultural activities dominate the economic activities in this union. *Pakuria* has an electrification rate of 3.3% whereas *Ichharkandi* has no electrification at all.

Study segment V3 is situated in Feni district, the former sub division of greater Noakhali. Feni lies between 22°44′ and 23°17′ north latitude and between 91°15′ and 91°35′ east longitude. It has 553 villages with around 27% of the population having no electricity (BBS, 2015). The sample villages *Betagi* and *Rasulpur* are under the Sonagazi upazila, which has a population of 2,35,000. Rural household size is 5.17, male-female sex ratio is 93 and literacy rate is 47% in this upazila. Economy is heavily based on agriculture and a good percentage of the adult male population work in other districts of the country as seasonal labourers.

To explore users satisfaction level with the existing mode of lighting and their willingness to switch to electricity supply from renewable hybrid mini-grid a five point Likert scale (1 as highly satisfied and 5 as highly dissatisfied) was used during the data collection. Michelsen and Madlener (2015) followed the same approach in Germany to identify homeowner satisfaction with newly adopted residential heating systems. Li, et al., (2013) studied rural farmers willingness to convert traditional houses to solar homes in Chongqing, China by applying Likert scale. Bond, et al., (2010) applied the same method studying community preferences and satisfaction in East Timor in relation to solar lantern and solar home systems. Only one such study carried out by Komatsu, et al., (2013) in Bangladesh explored the customer satisfaction with installed solar home systems. However, there is no available literature regarding user satisfaction with fuel-based lighting in Bangladesh. Findings of the survey undertaken in this research work help to justify the results of customers' willingness to pay for electricity from decentralized hybrid mini-grids.

3.3.2 Survey Questionnaire

The initial survey instrument was prepared based on the secondary data available in published sources and the Bangladesh government's official publications. To increase the scope and efficiency of the initial instrument several discussion meetings were conducted in the first few days of the field visit with the people involved in decentralized mini-grid or micro-generation business and professionals working in this sector in Bangladesh. Among these, the site manager of the Purobi Green Energy Limited (PGEL), Sandwip Island; the director of Sustainable Energy & Agro-resources Ltd (SEAL), Gazipur; Manager, Navana Renewable Energy Ltd., Dhaka and residential engineer of Feni Wind Power Plant, Feni were the most useful ones. The initial survey instrument was revised according to field experience gained through the discussion meetings. Two volunteers were included in all the discussion meetings, who subsequently participated in the filed data collection process. Involvement of two volunteers in the whole process enhanced the uniformity of the valuable primary data collection.

Proper ethical approval was obtained from the ethical approval committee of De Montfort University. The survey was conducted with maximum care to collect accurate data regarding respondents demographic information, income level and frequency, details of electricity or kerosene consumption, energy consumption pattern, level of satisfaction with current means of energy supply, intended energy usages, willingness to switch to proposed micro-grid and finally their willingness to pay for the renewable energy supply. At the end of household data collection in every study segment, local shop owners, irrigation pump owners, school(s) and other entities were interviewed to explore their electricity load demand.

To obtain the above-mentioned data through the field survey the target-oriented questionnaire (Appendix I) was finalized considering the socio-economic conditions of the non-electrified rural areas of Bangladesh. This final questionnaire contained five specific steps to serve the purpose. These are:

Step 1: To ease the whole interview process at first the scope and objectives of the study were briefly explained to the respondents. Once respondents were ready to answer the questions, data regarding their age group, gender, profession, income and access to electricity noted at the beginning of the interview.

Step 2: Based on the electrification status of the households, respondents were asked different sets of questions at this stage. Respondents having electricity supply either through Solar Home Systems (SHS) or diesel generator grouped as electrified households and continued with questions 3 to 11. On the other hand respondents using ***kerosene, pre-charged battery or solar lamp etc***. were classed as non-electrified households. For this group Q 3 to Q 11 were excluded, instead they were asked to answer Q 12 to Q 14. Through specific target questions at this stage, households (both electrified and non-electrified) energy usages and monthly costs were estimated.

Step 3: At this stage of the interview, all the respondents were asked to express their level of satisfaction with the current means of energy supply and if they wanted to switch to better electricity supply from renewable sources. Firstly household with SHS or diesel generator were asked if they wanted to switch to decentralized hybrid mini-grid (HMG) based electricity. Thereafter, non-electrified households were asked to express their level of preferences to switch to both SHS and HMG based energy supply.

Step 4: At this point of the interview process all the respondents were asked detailed questions (Q 15 to Q 21) to explore their electricity load demand and consumption pattern. Standard wattage of equipment was considered throughout this process and seasonal variations were carefully applied to calculate estimated load requirements.

Step 5: At this final stage of the interview respondents were asked specific questions to find out their willingness to pay (WTP) for the proposed electricity supply. While offering different bid prices (i.e. USD 0.40/kWh, USD 0.45kWh, USD 0.50/kWh) to the respondents the total amount of expected electricity cost based on the estimated load demand of a particular household was mentioned along with the unit price of energy. Further analysis of WTP was based on the monthly estimated cost of electricity corresponding to unit bid values. This approach offered the respondents to have more informed decision regarding their expected expenditure for the proposed electricity to avoid any bias in deciding maximum WTP.

Finally every respondent was asked if they were ready to pay a connection fee for the proposed electricity supply. Respondents, who answered yes to Q26, were further investigated if they were ready to pay the cost as one off or in instalment.

An acknowledgement card with a counterpart was issued to every respondent at the end of the interview expressing thanks for their valuable time and cooperation, which contained interview date, the respondents' serial number, village name and contact details of the researcher. The retained counterpart offers the opportunity for the researcher to track back the respondent if clarifications of the collected data are required at a later date.

3.3.3 Sampling of Respondents

Most of the households in rural Bangladesh are in a cluster of two to five or six houses under a specific title for the families (i.e. Choudhuri Bari, Mia Bari etc.) and do not bear any door number. Although individual households of a cluster may have different financial conditions they bear the same family title. Some single households have more than one families living under one roof and have separate cooking facilities or arrangements. Each of these families was considered as a separate household for the purpose of this study.

Samples were drawn randomly using the 'Random Number Generator' application (an IOS app to be accessed as free) on the mobile device. This app has the feature to select a range of houses in a cluster from one to hundred. House number one was assumed the first right hand side one of the cluster. A maximum of two to three houses were interviewed from each cluster. In case of individual or separate houses, the same 'Random Number Generator' app was used assuming house number one was the first house on the right hand side of a village road and number two the first one on the other side of the road.

3.3.4 Cost of Energy

To calculate the cost of electricity used by the few respondents included in this study who already have electricity supply through the SHS or diesel generator all the related data, i.e., capacity of the power generating equipment, initial investment, running cost, repayment if any, repair cost, equipment's expected life and energy consumption were collected.

As SHS's performance depends on the available sunlight and storage devices, average output of solar panel in Bangladesh has been estimated as 25% of the rated output (Khan and Khan, 2002). Therefore, the following equations were used to calculate the energy output of the system and actual energy consumed by the household.

Total energy output E_t = Peak kW x % average output x estimated sunny hours per year x System's life span

Total energy consumed E_c = Individual appliances x working hours (kWh)

In theory, COE is derived by applying the total energy produced by the system. However, as the current study revealed that households with SHS mostly use the energy only in the evening time through the battery backup, therefore the actual amount of energy used was taken in account to calculate the COE. The same principal was followed to determine the COE from the diesel generators as well. The following equation was applied for this purpose.

$$\text{Cost of electricity COE (USD/kWh)} = \frac{\text{Total cost (Cost of the system + Maintenance + Repair)}}{\text{Total amount of energy (kWh) consumed } (E_c)}$$

Total cost in the above equation refers to the lifecycle cost of the system. To calculate the amount of energy produced by the system, actual amount of energy consumed by the respondent and the COE during the interview specific formulae were set in Microsoft Excel to expedite the process during the field data collection.

It is important to mention that electrified households in rural Bangladesh use light bulbs and other equipment with a wide range of capacities. Therefore, actual capacity of each equipment was collected to estimate the amount of energy consumed and hence the cost of electricity (Table 3.5).

3.3.5 Level of Satisfaction and Willingness to Pay

Respondents were asked specific questions to express their level of satisfaction with the existing means of lighting, their willingness to switch to distributed mini-grid based renewable energy supply and finally their willingness to pay for the estimated usages of electricity. At the same time all non-electrified households were asked about their willingness to switch to SHS to explore their preferential choice between SHS and RMG (Renewable Mini-Grid).

To identify respondent's satisfaction level with the existing mode of energy supply for lighting and other equipment (if any) and willingness to switch to better quality electricity supply (SHS or RMG) a five point Likert scale ('1' as very satisfied or very much interested to '5' as very dissatisfied or not interested at all) was applied. Same approach was followed by Komatsu et al. (2013) to identify user satisfaction with the SHS in Bangladesh and by Li, et al., (2013) to explore rural Chinese farmers willingness to convert their conventional homes to solar homes. Using Likert scale in this instance offers the advantage of allowing the respondents to express their degrees of opinion instead of just answering yes or no. However, the major associated risk in this approach is that respondents may incline themselves in a positive light.

Before introducing questions related to willingness to pay (WTP) a brief idea was given to the respondents regarding the health and environmental issues of using conventional liquid fuel for lighting, general price comparison among kerosene based lighting, diesel generator, grid energy supply by Polli Bidyut Samitti and electricity supply from the proposed mini-grid. This information helped the respondents to make informed choice of responses, which in turn helps to avoid any bias. Respondents were informed of the approximate price of electricity from the renewable mini grids to be supplied at a rate of USD 0.40/kWh and the price of grid electricity dedicated to the village areas at a rate of UDS 0.13/kWh (Polli Bidyut Samitti, 2012). Although the mini-grid design part of this study (Chapter 4) shows that electricity price from the proposed hybrid renewable mini-grids can be supplied as low as USD 0.29 to USD 0.31/kWh, an initial bid (I_Bid) price of USD 0.40/kWh was offered to the respondents. The basis for offering USD 0.40/kWh was the unit price of electricity offered by one of the most successfully running decentralized solar-diesel hybrid mini-grid project in Sandwip Island, Bangladesh (Khan, et al., 2016).

To explore willingness to pay (WTP) the dichotomous choice contingent valuation method (CVM) was applied as this technique better captures use and non-use variables. CVM is a valuation technique based on market / customer survey where respondents have the opportunity to make an informed decision on the pricing of a good or service. Rahmatian (2005) described this method as the most suitable one for willingness to pay study as it captures the pricing options even in case of uncertainties and value service or good that is not currently available. On the other hand, Venkatachalam (2004) criticized CVM for the probable disparity between willingness to pay and willingness to accept or ability to pay. However, the field data collection technique applied in this research tried to minimize the possible bias by associating customers' financial status and their estimated consumption.

CVM approach was applied by Anjum (2013) to determine household's intention to switch to better domestic waste management services and their willingness to pay for such initiatives in the city of Islamabad, Pakistan. Herath, et al., (2012) also applied the same approach in Madhya Pradesh, India to explore consumer willingness to pay for better quality electricity supply. Many other researchers (Arega and Tadesee, 2017; Gou, et al., 2014; Twerefou, 2014 and Adaman, et al., 2011) also applied the CVM approach while studying customers' willingness to pay for electricity from renewable resources.

Four major determinants were tested towards respondent's intention to pay for proposed electricity supply from the mini-grids in this study. These are:

1. Better quality and more stable energy supply (compare to existing means)
2. Clean energy posing no health hazard
3. More income potential for family welfare
4. Cost saving in long run

Interative choice discrete type question was asked in the first instance if the respondents are willing to pay USD 0.40/kWh for the proposed energy supply. Respondents who accepted the first bid (USD 0.40/kWh) were asked if they were willing to pay more than the value of the first bid. Respondents refused the first bid were offered a lower bid. Eventually an open-ended question was asked using a five different bid sets (as in the survey questionnaire, Q. 23, Appendix-1). However, it was made clear that choosing lowest bid may not be realistic, as the mini-grid operator may not make enough profit to make the project viable for long run and selecting a higher bid might be beyond their financial capability. Finally the responses to the discrete choice questions were analysed by logit regression and open-ended maximum willingness to pay responses by multiple regression analysis using the SPSS software. Despite many advantages of the CVM approach, it is often criticized for different biases. To eliminate the starting bid point bias the pre-determined (as mentioned earlier) value of 0.40 was applied. To deal with the strategic bias the government supported private or public-private partnership of the proposed projects were mentioned and finally to overcome the hypothetical bias respondents were assured about the better quality service to be provided under the new renewable energy policy of Bangladesh Government.

Different socio-economic and demographic factors are related to respondent's willingness to pay. The mean willingness to pay for the proposed electricity supply was calculated by estimating the parametric model allowing inclusion of socio-economic factors as major determinants into the WTP function. These are the four major determinants mentioned earlier. Validity and reliability of the CVM results are more justified by inclusion of these factors and thus achieve more acceptances.

3.3.6 Logit and Multiple Regression Models

The logit regression function for determining WTP has widely been used by many researchers (Lal and Takua, 2006; Arene and Mbata, 2008 and Urpelainen and Yoon, 2015). Logit regression analysis approach was formulated as below assuming willingness to pay (WTP) as a dependent variable while others as independent variables.

$$\text{WTP} = f\,(I\_Bids + Age\_Gr + G\_MF + Income\_Gr + Income\_Freq + HH\_Size + HH\_EleStat + Load\_Expec)$$

Where, WTP the willingness to pay refers to respondents' dichotomous choice of yes or no corresponding to value '1' or '0' respectively. The independent variables of this model include initial bid (*I_Bids*) value as 40 and other vid values offered are 30, 45, 50 and 60. As a common market rule bigger values should have a negative relation with WTP. Age group (*Age_Gr*) assumed to have inverse relation with the WTP, as younger respondents in rural Bangladesh are more educated and are more open to accepting new technologies and services compare to their seniors. The entries for gender (*G_MF*) were made by coding '1' for male and '0' for female. Respondent's income level (*Income_Gr*) expected to have positive relation with WTP, as households with higher income tend to pay more for the service offered. However, income frequencies (*Income_Freq*) were grouped under two categories for this analysis. Respondents having both monthly and seasonal income were considered under the monthly income group, as these households are somewhat comfortable to pay monthly fees for the proposed electricity supply. Coding was applied as '1' for monthly income and '0' for seasonal income group. It is assumed that monthly income group are more likely to accept more WTP. Size of the household (*HH_Size*) is an important variable, which should have a negative relation with WTP. Electrification status (*HH_EleStat*) was classed as electrified households (SHS and Generator) and un-electrified households (kerosene, solar lamp, battery) and coded as '1' and '0' accordingly. Electrified households were expected to be less willing to pay for new electricity supply as they already have invested in energy generating equipment. Finally, the expected load demand (*Load_Expec*) of household has a complex relation with the WTP as because it is related to their income level as well.

$$WTP = \frac{1}{1 + e^{\ln zi}}$$

Where, $\ln zi = \alpha + \beta_0 I\_Bids + \beta_1 Age\_Gr + \beta_2\, G\_MF + \beta_3\, Income\_Gr + \beta_4\, Income\_Freq + \beta_5\, HH\_Size + \beta_6\, HH\_EleStat + \beta_7\, Load\_Expec + \mu i$

Maximum willingness to pay (WTPmax) value expressed by the respondents was specified as the multiple regression function related to different socio-economic characteristics. Therefore, WTPmax represents the maximum amount respondents willing to pay.

$$WTPmax = \alpha + \beta_1 Age\_Gr + \beta_2\, G\_MF + \beta_3\, Income\_Gr + \beta_4\, Income\_Freq + \beta_5\, HH\_Size + \beta_6\, HH\_EleStat + \beta_7\, Load\_Expec + \mu i$$

Where, μi is the disturbance term also referred as the random error term. Unobservable influence or effect related to a specific variable can be captured while calculating the WTP value

3.4 Results and Discussions

The demographic data collected in this fieldwork represent the decision-making individuals (or persons assigned to act on behalf of the decision makers) of the households. It is clear from this survey (Table 3.1) that important household decision making is dominated by the male (91.33%) and mature young age group (31-40 year old) represents the highest (50%) number followed by the 41-50 year age group (30.33%). Monthly earning of Tk. 6001-8000 group dominates (40%) income distribution across all the three study segments (Table 3.2 & Figure 3.2). Most of the households (47.33%) have only seasonal income and 32% have monthly income. However, the total of monthly (32%) and the both type (monthly and seasonal) income (20.67%) group constitute 52.67% of the respondents (Table 3.2). 39% of the households in study segments are characterised by 5-6 members in families and 29.33% households have 3-4 members in their families (Table 3.3). Demographic, income distribution and family size patterns across all three study segments are same.

	Gender		Age distributions						Total
	Male	Female	25-30	31-40	41-50	51-60	61-70	70+	
V1	91	9	6	48	31	14	1	0	100
V2	96	4	5	59	26	7	2	1	100
V3	87	13	9	43	34	11	3	0	100
Total	274	26	20	150	91	32	6	1	300
%	91.33	8.67	6.67	50%	30.33	10.67	2	0.33	100

Table 3.1: Gender and age distribution at different study segments

	Number of households and corresponding monthly income (Tk)								Total
	<4000	4000 to 6000	6001 to 8000	8001 to 10000	>10000	Monthly Income only	Seasonal income only	Both type Income	
V 1	16	27	35	12	10	21	54	25	100
V 2	23	21	39	13	4	39	41	20	100
V 3	13	19	46	13	9	36	47	17	100
Total	52	67	120	38	23	96	142	62	300
%	*17.33*	*22.33*	*40*	*12.67*	*7.67*	32	47.33	20.67	100

Table 3.2: Household monthly income distribution and income frequency

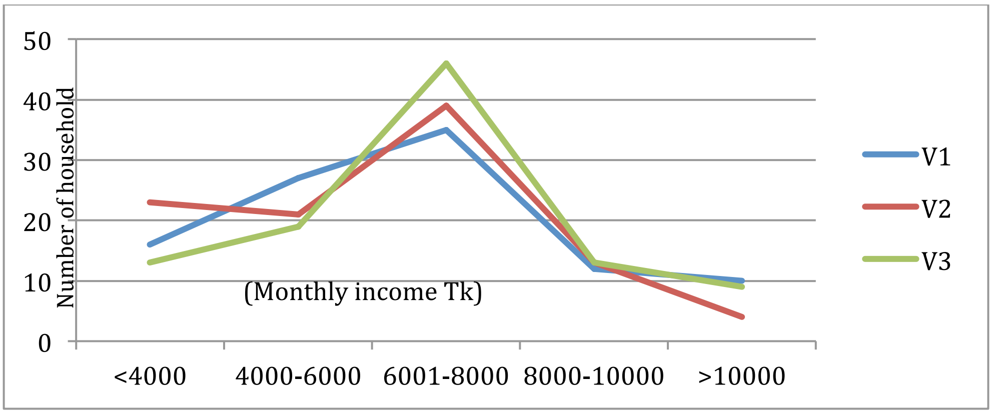


Figure 3.2: Household income distribution in three different study segments

	Number and size of households						Total
	2 People	**3-4 People**	**5-6 People**	**6-7 People**	**7-8 People**	**> 8 People**	
V1	2	33	28	25	9	3	100
V2	0	26	54	9	6	5	100
V3	3	29	35	22	7	4	100
Total	**5**	**88**	**117**	**56**	**22**	**12**	**300**
%	1.67	29.33	39	18.67	7.33	4	100

Table 3.3: Respondents' household size

Only thirteen households were found to be electrified in all study areas and the highest level of electrification was observed among the income group of Tk. 6001-8000 per month (Table 3.4). Wide difference in monthly consumption of electricity across different income group was recorded. The average lowest consumption was 3.60kWh and highest 33.76kWh per month for households with monthly income less than Tk. 4000 and more than Tk. 10,000 respectively (Table 3.5). While electricity prices varied among SHSs and diesel generators for individual installations, unit costs ranged between USD 0.77/kWh and USD 0.97/kWh for SHSs and between USD 0.82/kWh to USD 0.93/kWh for diesel generators. Notably, it was observed that electrical appliances (light bulb, fan, television etc.) used by the electrified households are not energy efficient. However, as the number of such households is comparatively small (13 households out of 360 samples) further research is required to make any conclusive remark in this regard.

	Electrified households					Total
	<Tk. 4000	Tk. 4000 – 6000	Tk. 6001 – 8000	Tk. 8001 - 10000	> Tk. 10000	
V 1	1	1	2	1	0	5
V 2	0	2	2	1	1	6
V 3	0	0	1	0	1	2
Total	1	3	5	2	2	13

Table 3.4: Electrified households across different study segments

Income level (BDT) monthly	SL	Family size (Number of people)	Source of energy	Equipment used	Average daily duration (Hours)	Average monthly Usages (kWh)	Unit cost (USD/kWh)	Average monthly Cost (USD)
< 4000	1	3	Gen*	2LB	3	3.60	0.87	3.13
4000 -	1	5	SHS	2LB, 1Aud	4	5.25	0.90	4.73
6000	2	6	SHS	2LB, 1TV	5	13.20	0.85	11.22
	3	6	Gen	2LB, 1Audio, 1TV, 1MC	6	18.96	0.82	15.55
6001 -	1	4	SHS	2LB, 1TV, 1Fan, 1MC	6	21.36	0.97	20.72
8000	2	7	SHS	2LB, 1TV, 1Fan, 1Aud, 1MC	5	18.72	0.83	15.54
	3	5	SHS	2LB, 1TV, 1Fan, 1MC	7	24.92	0.88	21.93
	4	6	SHS	2LB, 1TV, 2Fan, 1MC	6	20.60	0.87	17.92
	5	7	Gen	3LB, 1TV, 2Fan, 1Aud, 1MC	7	30.36	0.92	27.93
8001 -	1	5	SHS	2LB, 1TV, 2Fan, 1Aud, 1MC	8	26.40	0.77	20.33
10000	2	7	Gen	3LB, 1TV, 2Fan, 1Aud, 2MC	7	32.96	0.88	29.00
>10000	1	6	Gen	2LB, 1TV, 2Fan, 1MC	8	25.60	0.91	23.30
	2	8	Gen	4LB, 1TV, 2Fan, 1Aud, 2MC	7	33.76	0.93	31.40

* Connection from the neighbour's diesel generator

(Gen: Diesel Generator, SHS: PV Solar Home System, LB: Light Bulb 20 – 40Wt; TV: Television 80 - 120Wt; Aud: Audio Device 20 – 40Wt; Fan: Electric Fan 60 – 80Wt; MC: Mobile Phone Charger 8 – 10Wt)

Table 3.5: Detail electricity consumption pattern, usages and cost for individual electrified households

Dominance of kerosene (90.25%) as the main source of lighting is well evident among the non-electrified households in this study (Table 3.6). Only few people use solar lamp (3.48%) and batteries (6.27%). Energy consumption and number of lighting units increase with the higher income groups. Cost of kerosene lighting remains the lowest (USD 5.00/month) for the poorest (< Tk4000/month) and it reaches the highest (USD 12.95/month) for the affluent group having income of Tk8000-10000/month (Figure 3.3). Average highest duration of usages (3.64 hours a day) was observed among the second top income group (Table 3.6 & Figure 3.3). It is clear from Figure 3.4 that electrified households in the study areas use energy for lighting and other purposes for longer hours compared to the non-electrified ones. Regarding monthly energy expenditure families fitted with SHSs and diesel generators spend more than the families without electricity.

Income Level (Tk/month)	Source of lighting and Number of households			Average Usages		Average monthly cost (USD)		
	Kerosene	Solar Lamp	Battery	Lighting Units	Daily Duration	Kerosene	Solar Lamp	Battery
<4000	49	1	1	3.20	2.14	5.00	5.65	6.24
4000 - 6000	60	1	3	3.82	2.56	7.16	7.32	7.86
6001 - 8000	107	3	5	4.19	3.13	9.59	9.04	10.23
8001 -10000	28	3	5	4.34	3.64	12.95	11.71	12.35
>10000	15	2	4	4.45	3.53	11.50	10.14	12.21
Total	**259**	**10**	**18**					
%	90.25	3.48	6.27					

Table 3.6: Lighting usages and relative costs in non-electrified households

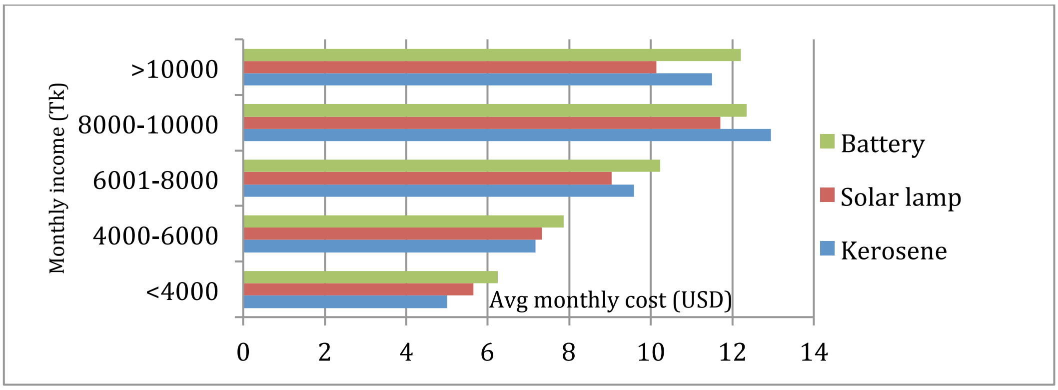


Figure 3.3: Average cost (USD/ month) of lighting in non-electrified households

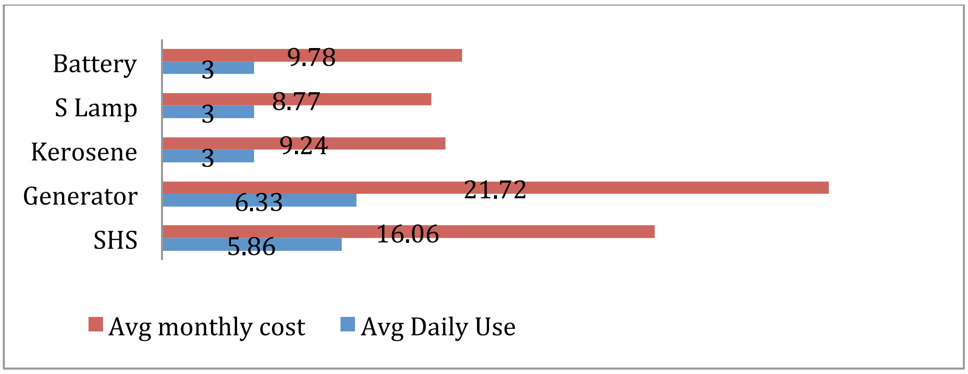


Figure 3.4: Energy usages trend (hours/day) and corresponding monthly costs (USD)

Non-electrified households using kerosene only for lighting purpose were asked to express their level of satisfaction and at the same time they were tested for their willingness to switch (WTS) to both SHS and RMG. Although the detail study of customer WTS to SHS is out of the scope of this research, it was briefly studied to compare it with the WTS value of RMG. The key reasons for their preferences were noted to justify the demand for the RMG. The highest mean satisfaction (3.51) with kerosene fuel for lighting was observed among the lowest income group (<Tk4,000/month) and the level of satisfaction level decreased with the increase in household income (Table 3.7 & Figure 3.5). Lowest mean satisfaction (1.63) was found with the highest income group (>Tk10,000/month). Figure 3.5 indicates customer's inclination of switching toward RMG. The linear mean WTS to RMG indicates a steady rise with increased household income (Figure 3.5). Respondents expressed their clear interest to get electricity from RMG rather than SHS as the mean value of WTS ranges from 3.67 to 4.86 for RMG across all income groups. The WTS to SHS had maximum and minimum mean value of 3.41 to 2.33, which do not represent a strong customer intension toward this technology.

Income level (Tk)	Total user Number	Mean satisfaction level	Willingness to switch to SHS (Mean)	Willingness to switch to RMG (Mean)
<4000	49	3.51	2.33	3.67
4000 - 6000	60	3.12	2.75	3.89
6001 - 8000	107	2.76	3.11	4.58
8001 - 10000	28	2.53	3.41	4.86
>10000	15	1.63	3.32	4.86

Table 3.7: Level of satisfaction with kerosene lighting in non-electrified households and willingness to switch to SHS and RMG

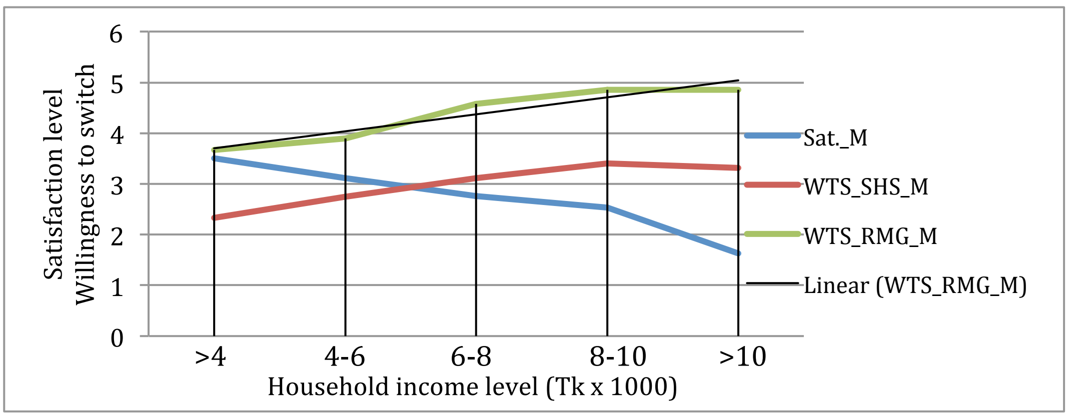


Figure 3.5: Mean customer (using kerosene only) satisfaction level and willingness to switch (*Sat_M; Mean Satisfaction level; WTS_SHS_M: Mean Willingness to switch to Solar Home System; WTS_RMG_M: Mean Willingness to Switch to Renewable Mini-Grid*)

Table 3.8 shows that households using SHS are more satisfied (mean satisfaction 3.73) with their systems than those using diesel generators (mean satisfaction 2.82) and on the other hand the battery users had higher mean satisfaction (3.64) than the solar lamp users (mean satisfaction 3.23). Lower mean satisfaction levels with current means of lighting correspond to higher MWS to RMG (Table 3.8 & Figure 3.6). The linear mean WTS indicates strong customer switching intention to RMG from diesel generator (mean WTS 3.95), solar lamp (mean WTS 4.73) and battery (mean WTS 4.82). However, the mean value of 2.35 representing customer WTS from SHS to RMG indicates poor intention level of switching.

Type of household	Mean satisfaction level	Mean willingness to switch to RMG	Sample (n)
SHS	3.73	2.35	7
Diesel gen	2.82	3.95	6
Solar lamp	3.23	4.73	10
Battery	3.64	4.82	18

Table 3.8: Mean customer (solar lamp, SHS, diesel generator and battery) satisfaction and willingness to switch to renewable hybrid mini-grid

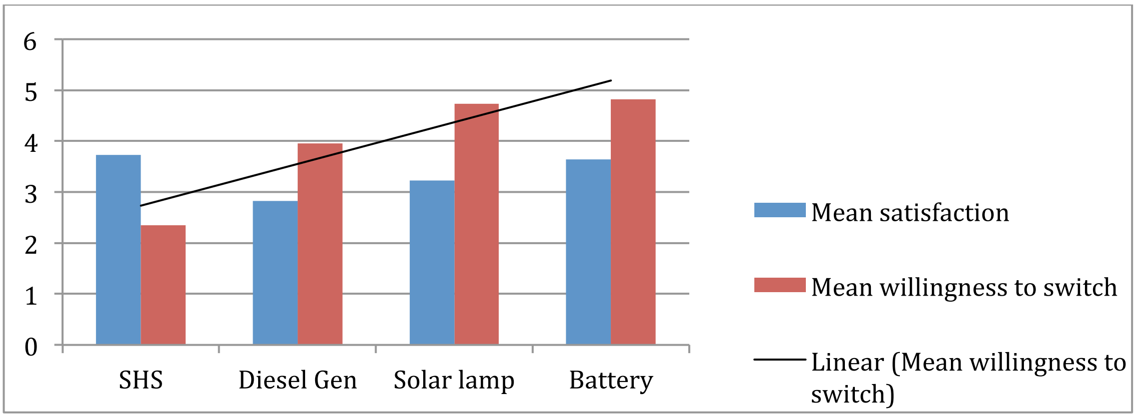


Figure 3.6: Customer (solar lamp, SHS, diesel generator and battery) mean satisfaction and willingness to switch to renewable hybrid mini-grid

Respondents were given opportunity to make informed decision regarding their expected electricity load demand to be supplied by the proposed hybrid mini-grid.

Daily maximum and minimum estimated load for day and evening usages were calculated carefully. Households showed comparatively very low demand during the day (Table 3.9). Daytime monthly minimum load ranged from zero to 2.92kWh and maximum load ranged between zero and 3.46kWh. The lowest income group (<Tk4000/month) expressed no intention to use electricity during the daytime. However, households tend to use most of the expected load during the evening. Household maximum monthly load requirement for evening time ranged between 5.04kWh and 24.38kWh and minimum load demand varied from 3.72kWh to 19.94kWh. Increased electricity demand was observed with the higher income groups. The mean expected demand of electricity from the mini-grid was estimated to be 18.863kWh/month/household (Table 3.9).

The current monthly load consumption by the electrified households (calculated from table 3.5) has been compared to the maximum expected load demand by all households in figure 3.7. Bottom two income groups (<Tk4000 and Tk4000 - 6000 per month) showed slightly higher expected load demand than the current consumption by the electrified households of the same income level. Whereas, top three income groups represent less expected consumption (between 22.8kWh and 27.84kWh/month) in comparison with the actual current consumption by the electrified households (between 23.2kWh and 29.68kWh/month).

It is clear from figure 3.8, that monthly expected cost of proposed electricity (to be supplied @ USD 0.40/kWh) remains low for all households than the current spending for energy by both the electrified and non-electrified households (calculated from table 3.5 & 3.6).

Identifying the non-domestic load requirement is complex in nature. Irrigation pumps represent substantial load demand (15.75kWh/d and 17.54kWh/d) but load is restricted only for few months (September to February). On the other hand local businesses offer good amount of daily load requirement throughout the year (Table 3.9a). Shops tend to consume less energy during the daytime, whereas schools and other establishments (i.e., community centres, union office) use electricity only in the daytime.

Income level	Monthly household average expected load demand (kWh/ household)						
	Minimum		Total	Maximum		Total	
	Day	Evening		Day	Evening		Mean demand
<4000	0	3.72	3.73	0	5.04	5.04	
4000 - 6000	0.48	5.64	6.12	1.14	12.3	13.44	
6001 - 8000	2.40	17.60	20.03	2.62	20.18	22.80	18.864
8001 - 10000	2.84	20.68	23.52	2.84	22.36	25.20	
>10000	2.92	19.94	22.86	3.46	24.38	27.84	

Table 3.9: Expected domestic load demand by the non-electrified households

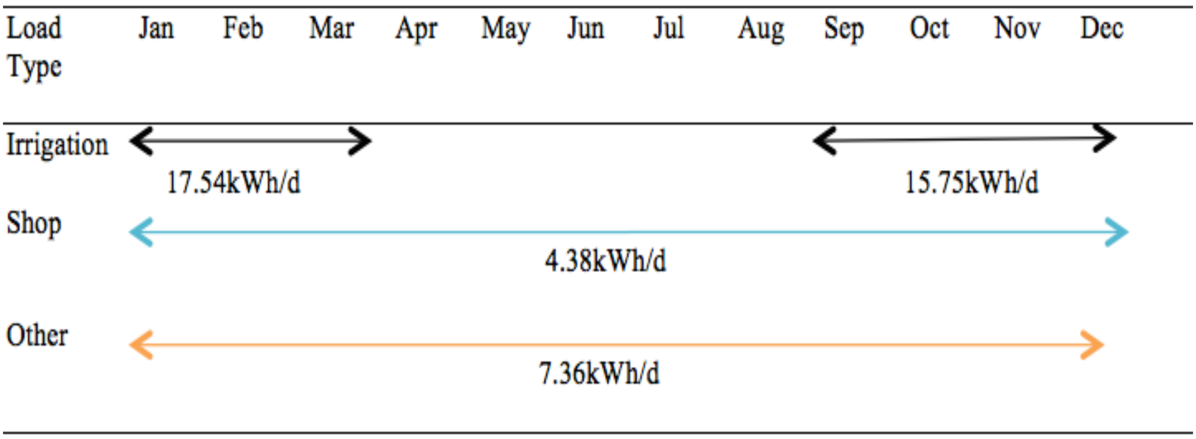


Table 3.9a: Estimated total maximum average irrigation, business and other loads

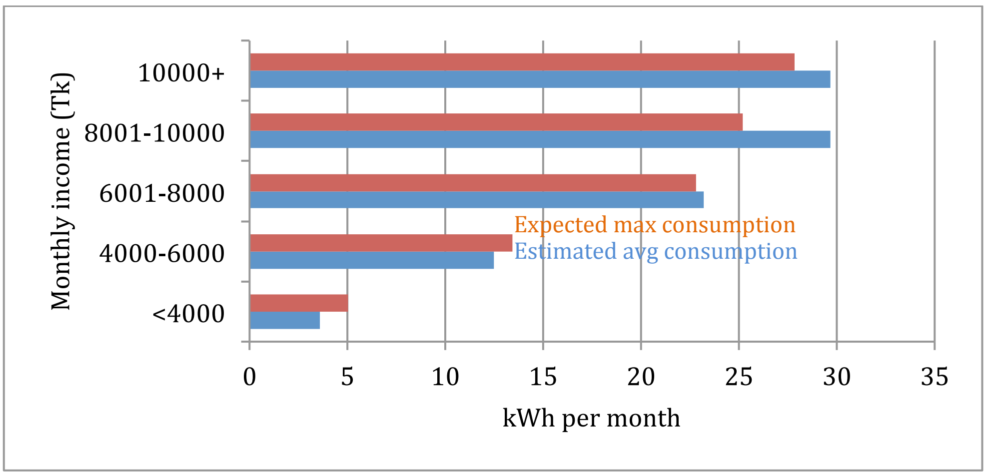


Figure 3.7: Monthly average calculated consumption (kWh) by the electrified households and average expected maximum consumption (kWh) by non-electrified households

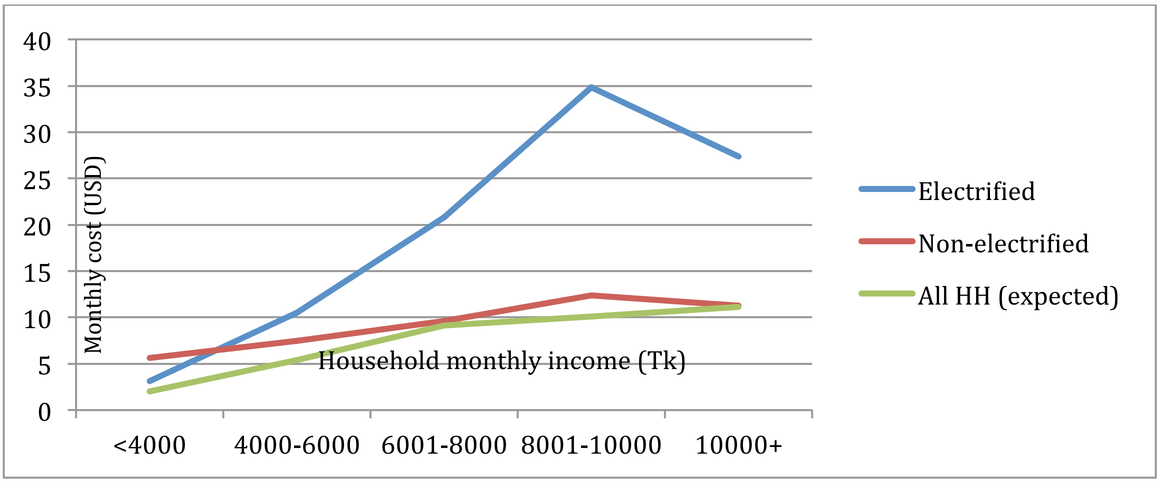


Figure 3.8: Current cost of energy used by the electrified (SHS, Diesel generator), non-electrified (Kerosene, Solar lamp, Battery) households and the expected cost electricity to be supplied to all households by the RMG at a cost of USD 0.40/kWh

Based on the consumer income level and expected electricity load requirement, connection types from the proposed mini-grids can be classed in five major categories (Table 3.9b) as *Bottom user, Basic user, Medium user, Large user and Large plus user*.

User category	Income level (USD/month)*	Min & Max load demand (kWh/month)	Cost range (USD/month)	Cost as % of income
Bottom	< 50	3 - 5	1.2 - 2	2.5 - 4
Basic	51 - 77	5 - 13	2 – 5.2	4 – 6.76
Medium	78 - 103	13 - 20	5.2 - 8	6.76 – 7.78
Large	104 -128	20 - 25	8 - 10	7.78 – 7.81
Large plus	> 128	23 - 28	9.2 – 11.2	7.19 – 8.76

*Income in BDT converted to USD (1 USD = 78Tk)

Table 3.9b: Customer categories and their monthly cost of electricity against expected load

Regarding an initial payment as connection fee of Tk3000 (USD 38.6) per household respondents expressed different views (Table 3.10). The lowest income group (<Tk4000/ month) had the least willingness (24%) to pay the connection fee followed by (32%) the income group earning Tk4000-6000/month (Figure 3.9). Respondents with higher monthly income tend to have more acceptances to pay for the proposed connection fee. However, more respondents (mean 59.4) showed positive intention to pay the connection fee. Respondents who agreed to pay this fee, showed firm tendency (mean 82.80) to pay it by instalments. Only a small portion of respondents intended to

pay the connection fee as one off payment, which represents a mean value of 15.52 (Table 3.10). Figure 3.10 shows that instalment payment is dominated as a choice over the one off payment across all the income groups.

Income level	Yes (%)						No	
		Mean	One off	Mean	Instalment	Mean		Mean
<4000	24		0		100		76	
4000-6000	32		6.25		93.75		68	
6001-8000	67	59.4	13.30	15.52	86.70	82.80	33	40.6
8001-10000	86		24		66		14	
10000+	88		32.45		67.55		12	

Table 3.10: Respondents willingness to pay connection fee for electricity supply from the proposed RMG

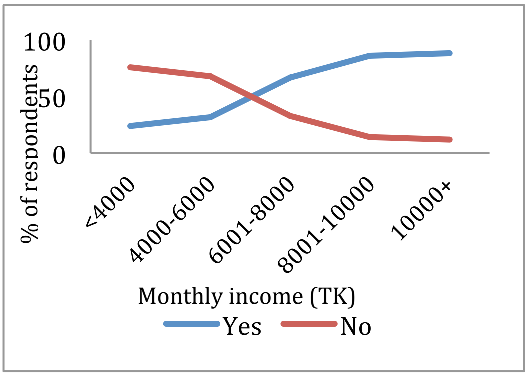


Figure 3.9: Respondents' willingness to pay for one off connection fee

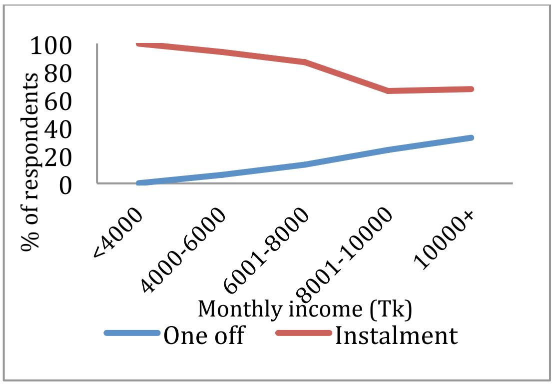


Figure 3.10: Respondents' preferred mode to pay for connection fee

Responses by the households related to some important variables have been presented in table 3.11 as overall percentage while studying customer WTP for this study. As household decision-making is dominated by the male (Table 3.1), the 87% WTP by the male respondents indicates a very positive attitude of villagers towards accepting the proposed unit price of electricity from the renewable mini-grid (Table 3.11). The dominant income (Tk 6001-8000/month) and age group (31-40 years) showed a very high interest (38.33% and 48.67% accordingly) in WTP for better quality energy sourced through the RMG. Respondents currently using kerosene for lighting purpose are very keen (83.33%) to pay for electricity regardless of expected monthly household load demand.

Variables (%)	Willingness to pay (%)	Un willingness to pay
Gender and WTP		
Male	87.00	4.33
Female	08.00	0.67
Income level and WTP (in TK)		
<4000	14.44	3.34
4000-6000	20.00	2.33
6001-8000	38.33	1.67
8001-10000	12.00	0.67
>10000	07.33	0.33
Age group and WTP		
25-30	05.67	1.00
31-40	48.67	1.33
41-50	29.67	0.67
51-60	10.00	0.67
61-70	01.66	0.33
70+	00.33	0
Household lighting and WTP		
SHS	01.33	1.00
Diesel generator	01.33	0.67
Kerosene	83.33	3.00
Solar lamp	02.67	0.67
Batteries	05.67	0.33
Expected load demand and WTP (kWh/month)		
5 -10	14.00	2.67
> 10 - 15	23.00	1.33
> 15 - 20	34.33	1.00
> 20 – 25	13.67	1.00
> 25 – 30	08.33	0.67

Table 3.11: Willingness to pay related to different variables

Respondents were asked to express their level of willingness to pay for electricity from the proposed mini-grid based on four key determinants using the open ended bidding game (Table 3.12). In this process every respondent was given opportunity to choose their WTP value for all bid values against different determinants. Although high number of respondents (62% to 76%) expressed their willingness to pay the lowest bid (USD 0.40/kWh) considering all the determinants, more number of respondents intended to pay two relatively higher bids (bid 40 and bid 50). However, a steady decline in WTP was observed for the top two bids (bid 50 and bid 60) regardless of any key determinants (Figure 3.11). Cost saving and income potential were the most chosen determinants in the top ranked WTP as USD 0.40/kWh by the respondents (Figure 3.11).

Determinants Variables	WTP (%)	Bid 30	Bid 40	Bid 45	Bid 50	Bid 60
Better quality and	Yes	76	88	81	34	13
stable supply	No	24	12	19	66	87
Clean energy, no	Yes	65	86	77	41	21
health hazard	No	35	14	23	59	79
Income potential	Yes	69	91	82	36	11
and family welfare	No	31	9	18	64	89
Cost saving	Yes	62	94	76	43	19
	No	38	6	24	57	81

Table 3.12: WTP bidding game results based on four key determinants

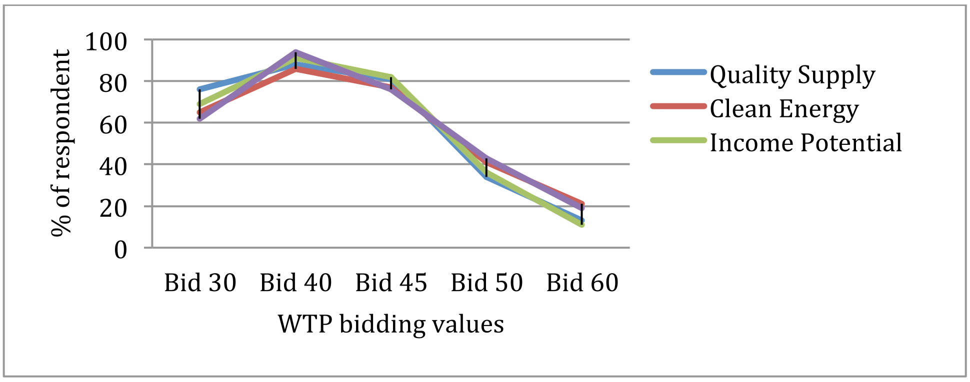


Figure 3.11: Key determinants and respondents WTP for different bid values

The logit regression and multiple regression values of different variables related to respondent's willingness to pay are presented in table 3.13. Respondent's age distribution shows negative relation with their willingness to pay values. The age group (Age_G) coefficient (-0.404623) suggests that unit increase in age (5years) tends to decrease the WTP by 0.405 units. This describes the phenomenon that if a group of respondent aged 30 years tend to pay USD 0.432/kWh, the WTP by the 35-year age group will be USD 0.426/kWh. It is clear that increase in age negatively affects the WTP but the magnitude is not very big. However, the odds interpretation of antilog coefficient 0.456 indicates that respondents are 0.456 times unwilling to pay for electricity from the mini-grid with an increase in age group. In the case of gender no significant relationship was observed between respondent's sex and their WTP.

Household income considered as a very important variable as the coefficient value of 0.003134 indicates positive relation with the WTP. In case of one unit increase in respondent's income the average maximum willingness to pay increases 0.0031 units. The effect of income as studied under different income groups (Income_G) is significant at 1%, 5% and 10% level of significance. The odds interpretation of antilog coefficient of 1.00162 suggests that respondents with higher income are more likely to pay for the electricity from the proposed mini-grid. It is interesting that income frequency (Income_Freq) shows no significant relation (coefficient value 0.512314) with the WTP.

The coefficient value of -5.714351 for the variable HH_Size (household size) indicates that unit increase in household size will have the respondent's average maximum willingness to pay (WTPmax) decreased by 5.71 units. For instance, a respondent with five members in family willing to pay USD 0.432/kWh, will reduce their willingness to pay to USD 0.373/kWh in case their family size increases to six. This negative relationship is significant at 1 percent and 5 percent level of significance. The odds interpretation antilog of coefficient 0.1243 suggests that if the size of household increases respondents become 0.124 times unwilling to pay for the electricity from the mini-grid.

The household electrification status (HH_EleStat) coefficient (-18.1024) represents a crucial negative relationship with respondent's WTP. If all other variables are maintained constant the households having electricity supply from SHSs or diesel generators are willing to pay 18.102 units less than the households with no electricity supply. However as the number of electrified households in this study is too small to make a conclusive remark, further research is recommended in this aspect.

Variable	Logit regression			Multiple regression	
	Coefficient	Odds ratio	Prob.	Coefficient	Prob.
Age_Gr	-0.073842	0.456131	0.2434	-0.404623	0.6821
G_MF	1.573621	6.321524	0.0569	-1.627342	0.8172
Income_Gr	0.000132	1.000162	0.0006*	0.003134	0.0000*
Income_ Freq	0.512314	1.624315	0.4527	-7.726213	0.2737
HH_Size	-0.781523	0.124291	0.0037*	-5.714351	0.0067*
HH_EleStat	1.231426	0.214123	0.0721	-18.102461	0.2342
Load_Expec	1.812461	2.182421	0.0273*	2.125672	0.0049*
I_Bids	-0.031424	0.921426	0.0000	--	--
Logit mean dependent variable	*0.415200*	*Mean dependent variable*	*0.4321*	*R Squared*	*0.55432*

Table 3.13: Regression results for the different study variables related to willingness to pay

The regression analysed WTPmax indicated an average value of USD 0.4321/kWh for the electricity to be supplied from the proposed decentralized renewable hybrid mini-grids. However, maximum willingness to pay value not necessarily be the optimal ability to pay for the electricity in the case of rural Bangladesh. The estimated WTP value for a product or service should reflect the consumer's ability to pay (Russell, 1996). In some cases WTP may exceed the limit of the actual ability to pay. When consumers believe that acquiring a product or service is a necessity to uplift their social status, life style and economic condition, they are ready to pay more than their actual capacity. In such cases they have to squeeze expenditure on other items to maintain their commitment. Therefore, the relationship between WTP and ability to pay poises is a matter of debate and demands to clearly distinguish these two notions (Maratia, et al., 2006).

3.5 Conclusions

The estimated average maximum willingness to pay value of USD 0.432/kWh for electricity supply from the proposed renewable hybrid mini-grid indicates that the tariff rural customers ready to pay would support a sustainable business model for good return on investment. Strong customer willingness to switch to mini-grid (mean value 3.67 to 4.86 across all income groups) counter-balances the relatively poor mean household monthly load demand (18.864kWh). However, the load management through efficient storage solution remains the main challenge as poor daytime domestic consumption has been identified through the current fieldwork. Fortunately, daytime agricultural and commercial load will offset the poor daytime domestic load. The combined managed load, which requires consumer consultation and rewarding schemes to defer partial evening loads to the daytime and adding more electricity consumption (switching village diesel water pump to RE electricity, local businesses and cottage factories etc.) in the daytime is the light at the end of the tunnel. This study revealed that this could be successfully done through customer counselling and education.

Findings of the field data collection presented in this chapter, i.e. estimated domestic, agricultural and other load profiles; households' willingness to switch to mini-grid based electricity and their willingness to pay for electricity build a strong base for cost effective mini-grid design with realistic load profile and selection of suitable business model for Bangladesh in the following chapters.

Note:

1. Refers to a level of energy consumption that is insufficient to meet certain basic needs to support economic and human development (Gonzälez-Eguino, 2015).

Chapter 4

Hybrid Mini-grid Designs for Bangladesh

Chapter Highlights

This chapter focuses on area specific renewable hybrid mini-grid designs for rural Bangladesh. Based on the renewable energy resource availability explored in chapter-2 and rural market characteristics with actual electricity load requirement analysed in chapter-3 some optimized hybrid systems have been designed and analysed. Designing area specific optimum systems while maintaining the minimal cost of energy production has been the key in selecting the wining systems. Suggested hybrid systems have been further analysed for standardization, which can in turn enhance upscale the diffusion of this electrification approach.

Chapter 4

Hybrid Mini-grid Designs for Bangladesh

4.1 Introduction

Numerous renewable hybrid mini-grids have been designed and implemented to substitute central grid in rural and remote areas around the world. The governments own most of the mini-grids either funded by themselves or by donor agencies and development partners. There are few public-private funded projects in some countries. However, private funded commercially viable hybrid mini-grids are very rare or non-existent. Question arises while thousands of standalone diesel mini/micro-grids are successfully operating and supplying very high cost electricity by private investors in many power starving developing nations, why renewable mini-grids cannot do the same? Although very high initial investment associated with the renewable mini-grid implementation and operation remains the key factor in this case, there is no conclusive answer to this question. The nature of the diffusion criteria is complex and therefore many issues related to the existing policy framework, regulatory environment, technical and financial states need to be addressed. A conventional Wind-Solar mini-grid requires battery bank, standby diesel generator (optional), electricity controlling and converting technologies besides the wind and solar components, whereas a diesel-based mini-grid essentially needs just a generator. However, optimized hybrid mini-grids require much lower operating cost compared to same size diesel generator. Therefore, correct financing tool and successful operation remain as the real challenges for market diffusion of such renewable technology.

Proper investment approach and optimum hybrid system design for a specific location to serve a required load are the key elements to be dealt with for operating a mini-grid successfully. As the target market for the proposed mini-grids in this research work are mostly the poor rural and remote areas of Bangladesh, financing the projects still remains as a major challenge. Although government's renewable 'energy policy 2008' supports such renewable mini-grids and provides backing with subsidies and low interest capital funding, no real market diffusion of this technology has been evident yet in Bangladesh. A few initiatives of subsidized private investment in such renewable projects reported to be failed in the recent years (discussed in detail in Chapter 5 of this research work).

Component sizing and combination of a mini-grid mainly depend on the availability of renewable resources and required load and load pattern. Most of the load profiles in rural areas are concentrated in the evening, which either need to be served by the battery bank or by diesel generator, which increases the project cost and hence the cost of electricity. During the field data collection (Chapter 3), potential daytime electricity loads (daily and seasonal) have been identified which can offer effective combined loads towards sustainable hybrid mini-grid implementations.

This chapter represents the design and analyses of various combinations of renewable hybrid mini-grids serving different load profiles at different locations considering the actual socio-economic factors and existing policy framework. To identify the suitable mini-grid designs a wide range of hybrid systems under three different groups (Group1, 2 & 3) has been studied. Group-1 hybrid systems cover five different locations, Group-2 covers two different locations and Group-3 covers the whole coastal region of the country. The study areas selected for this study represent the whole off-grid areas of Bangladesh.

4.2 Methodology:

4.2.1 Resource Data and Project Locations

It is clear from the potential renewable resources study in Chapter-2 that PV based mini-grids can be deployed across all the off-grid areas of Bangladesh. However, for the purpose of this study solar, wind, biomass (especially rice husk), and micro hydro have been taken into account as the potential renewable energy resources to design decentralized hybrid systems. Although wind, biomass and micro-hydro resources are very much limited in few off-grid areas of the country, combination of these RE resources (wind, biomass and hydro) can complement PV application in some cases. The detail renewable resource availability analysis in chapter 2 (section 2.3) has been used as the decision making tool to choose the resource and technology combination for any non-electrified site for hybrid mini-grid application. The time series data for solar radiation and wind speed were gathered for the analysis tool using the database of NREL (National Renewable Energy Laboratory, USA) and WindNavigator (AWS Truepower, New York) accordingly. Standard GIS data were double checked with the collected secondary data for validation. While NREL database provides specific GHI (Global Solar Irradiance) for any required geographical co-ordinate in Bangladesh, the WindNavigator database provides the most accurate up-to-date wind resources at different heights for any given location (excluding some islands off the cost of the Bay of Bengal) in Bangladesh. For biomass this study only considered the rice husk as the renewable resource. Although, small or micro-hydro resources are very limited and reported to be available mainly in the hilly areas of the country, one of the mini-grid sites was selected with such renewable resource.

While selecting sites for hybrid mini-grids for this study only the non-electrified villages, coastal areas, islands and remote hilly areas were considered. 150 representative locations were proportionately selected from the BPDB's electrification database and BREB's service area coverage database. 40 of these pre-selected sites were from *coastal areas*, 30 sites from *Hill Tracts* and 80 sites from *plain lands*. Finally seven study locations (Figure 4.1) were selected randomly out of these 150 pre selected off-grid sites from three major geographical regions. Seven selected study locations were:

- Ukhia, Cox's Bazar *represents Wind /+ Solar potential*
- Chakaria, Cox's Bazar *represents Wind /+ Solar potential*
- Kutubdia, Cox's Bazar *represents Wind /+ Solar potential*
- Baghaichari, Rangamati *represents Wind /+ Solar potential*
- Mainemukh, Rangamati *represents Micro Hydro /+ Solar potential*
- Santal, Rangpur *represents Rice Husk /+ Solar potential*
- Naogao *represents Wind /+ Solar potential*

However, for uniform representation of site samples while covering the whole country, the geographical location and RE (renewable energy) resources resemblance were maintained with the areas used for field data collection in the previous chapter (Chapter 3). For example, Cox's Bazar, Kutubdia and Ckakaria were selected as potential regions for wind and solar resources to cover the whole southern coastal areas and islands; Rangamati represents the whole Hill Tracts of the country featuring wind-solar and solar-micro hydro resources. Naogao and Rangpur represent the rest of the country being rich in solar resources and at the same time the areas with abundance of rice husk.

4.2.2 Designing Hybrid Mini-grids

Use of hybrid mini-grid system design software simplifies the whole process of data input, data analysis and selection of system configurations. With the provisions of time series renewable resources data and load demand pattern input along with related economic data and sensitivity variables some of the hybrid system analysis tools offer the wider scope of optimization. Most commonly used software are RETScreen, HOMER, PV*SOL, Hybrid2, TRANSYS, SAMS and MATLAB. Among all these HOMER has been most widely used across the world having some unique features, such as:

1. Ease of application
2. Wider scope of renewable resources input and their possible combinations
3. Greater selection of system architecture and dispatch strategies
4. Capability to compare DC and AC coupled systems
5. Provision of financial subsidy value input

Therefore, the 'Hybrid Optimization Model for Electric Renewables' (HOMER) micro-grid designing software (pro version) has been used in this study to design the hybrid system configuration consisting different components, i.e. solar PV, wind turbine, micro hydro, diesel generator, biomass gasifier, converter and lead acid batteries as energy storage. This software has successfully been used around the world by many researchers (Bhattacharyya, 2015; Sen and Bhattacharyya, 2014; Chukwuma, et al., 2015; Chattopadhyay, et al., 2015 and Kassahun, 2015) and it is the most widely used simulation platform for hybrid mini-grid design.

While HOMER suggests the best optimized model design for the given specific load, resources, economic inputs, system control features, constraints and sensitivity variables, it also suggests the lifecycle cost of the system as the total net present cost (NPC). This single value includes all costs and revenues that occur within the project lifetime, having future cash flows discounted to the present. Although the levelized cost of energy (LCOE) is often a convenient metric with which to compare the costs of different systems, HOMER uses the total NPC instead as its primary economic figure of merit. In its optimization process and ranks the system configurations according to NPC rather than levelized cost of energy. HOMER uses the following equation to calculate the total net present cost:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\ (i, R_{proj})} \quad (1)$$

Here, annualized cost is denoted by $C_{ann-tot}$; discount rate (rate of net yearly interest) by i; lifespan of the project by R_{proj} and capital recovery factor by CRF.

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (2)$$

Here, i denotes yearly real interest rate, N denotes specific number of year.

Finally, HOMER uses the following equation to calculating the COE:

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \quad (3)$$

Where, $C_{ann,tot}$ is the total annualized cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and $E_{grid;sales}$ is the amount of energy sold to the grid per year (*for this study* $E_{grid;sales}$ *value is zero* as systems considered here are not grid connected or ready to grid connect). The levelized cost of energy is therefore the average cost per kWh of useful electrical energy produced by the system but not the amount of energy utilized by the end users.

Due to the area specific limited diurnal availability of renewable resources all decentralized hybrid mini-grids should have power storage facilities. Large commercial

Lead acid batteries are widely used as a matured and known technology. While designing hybrid systems for this research, the dispatch strategy applied for battery bank is rather the 'load following' than the 'cycle charging' one, where only the renewable components charge the battery. Designed systems also have the facility to apply the cycle charging in case the RE technology fails. This approach ensures uninterrupted electricity supply by using the excess power of the generator to charge the batteries.

During the simulation process HOMER first determines if the proposed hybrid system combinations are feasible by checking the capability of every single component to satisfy the required load. Selected systems are then weighed against every economic and technical constraints imposed to ensure the sustainability at the initial stage. Performance of a hybrid system analysed by HOMER for a year is assumed to be the representative over the lifetime of the project. However, in reality system components lose their initial performance with aging. Therefore, such effects have been dealt in this research by using different sensitivity analyses during the system design process.

4.2.3 Hybrid System Economic Analysis

In sensitivity analysis, HOMER analyzes the net present cost (NPC) of a system to represent its lifecycle cost. While calculating the NPC HOMER considers all the costs related to:

- Cost of technology (renewable and non-renewable components)
- Replacement cost (at different stages of the project)
- Cost of diesel (if generator is added)
- Sales or purchase of electricity (to / from the grid, if connected to grid)

Although levelized cost of electricity (LCOE) has many critics it is generally used to compare the hybrid systems with same configurations. However, the net present cost (NPC) is applied by HOMER to compare the techno-economic performance of hybrid systems. Therefore, in optimization results HOMER positions the projects based on the NPC rather than considering their LCOE.

Hybrid system component costs were standardized based on the current suppliers[1,2,3,4] price and availability of the equipment in the local market (Table 4.1) while complying with quality standard required by IDCOL.

Components (Generic)	Investment cost (USD)	Replacement cost (USD)
PV	1600/kW	1200/kW
Wind Turbine	3000/1kW 8000/3kW 10,000/5kW	2000/1kW 6000/3kW 8,000/kW
Battery (Lead acid)	175/unit (6V, 225-360Ah)	150/unit (6V, 225-360Ah)
Generator (Diesel)	500/kW	400/kW
Converter	250/kW	200/kW

Table 4.1: Cost of different hybrid system components

The total project life has been applied as 20 years for lifecycle cost analysis using HOMER along with PV 25 years, generator 20 years, wind turbine 20 years, battery 5-10 years (depending on actual state of charge) and converter 20-25 years. Dealing with the power generation share of components and battery charge states HOMER picks the optimal life span of the system components and hence offers the proposed project lifetime.

Risk and uncertainty analysis are very important for the successful implementation, operation and maintenance of renewable energy project. Arnold and Yildiz (2014) applied the Monte Carlo Simulation (MCS) approach based on the complete lifecycle of a renewable energy project for its investment risk analysis. They claimed that this approach has advantages related to the contents and methodologies compared to the standard sensitivity analysis and net present value (NPV) estimation. Bergek et al., (2013) argued that common financial forecasting by analyzing the perceived risks and returns may fail to capture the total variety of factors that influence the private investors decision making process in renewable energy projects. They applied the approach that considers the whole spectrum of cost, uncertainties in the market and political issues. Chassot et al., (2014) followed the same approach and identified the perceived policy related risks as the major factors foe investment decisions.

1. Rahimafrooz (http://www.rahimafrooz-solar.com)

2. Navana Renewable Energy (http://www.navanapower.com/index.html)
3. Green Energy Solution Limited (House 11, Road 4, Banani, Dhaka, Bangladesh)
4. Netlink2 Traders (http://www.raxxesglobal.com/where%20to%20buy.htm)

For the purpose and scope of this study uncertainty studies have been performed using HOMER at the same time of modelling the projects. Uncertainties in key variables i.e., fuel price, battery lifetime, operation and maintenance cost, consumption (load) pattern can pose substantial risk on the success of the project. To serve this purpose, in sensitivity analysis multiple key constraint variables (values) have been applied for determining their effects on a specific hybrid system's techno-economic performance.

Various levels of subsidies and interest rates on capital investment have been applied with different mini-grids designed and analyzed in the following sections of this chapter (Hybrid Mini-grid Group-1 to 3). Optimization and sensitivity results obtained through the HOMER have been further analyzed and compared to the available performance data of existing mini-grids in operation, to suggest sustainable business model.

4.3 Proposed Mini-grid Design and Analysis

While designing a proposed mini-grid different end users demand patterns need to be carefully considered including the following points:

1. Hourly load distribution
2. Diurnal load variations
3. Seasonal variations in domestic, agricultural and commercial load
4. Socio-economic condition of the study area

Considering all the above factors sustainable techno-economic models need to be designed to make the mini-grids feasible to operate successfully. While designing the hybrid system the seasonal load demand and electricity production by different components were synchronized considering the local socio-economic conditions. For the purpose of this study consumer's electricity demand data, their income distribution and expected demand data from chapter-3 (Table 3.2; 3.9; 3.9a and Figure 3.7) were applied to formulate load pattern for the hybrid systems of different sizes at different locations.

Depending on the terrain, population density and load demand, actual size of the mini-grid may vary covering a specific service area. Based on the collected data (Chapter 3) various hybrid mini-grid model designs and their performance analyses were carried out in three major groups to identify optimal hybrid systems for different locations (Figure 4.1) covering all techno-economic aspects. Group-1 covers the wider range of geographical areas and renewable resource mix. Study sites included in this group are Cox's Bazar (Ukhia), Rangamati (Baghaichari & Mainemukh) and Rangpur. Group-2 includes Cox's Bazar (Chakaria) and Naogao. Finally, Group-3 sites (Kutubdia Island, Chakaria coast and Sandwip Island) represent the whole off-grid coastal areas of the country. All hybrid systems studied for these sites have been described in detail with their corresponding design, performance and economic output in the sections below.

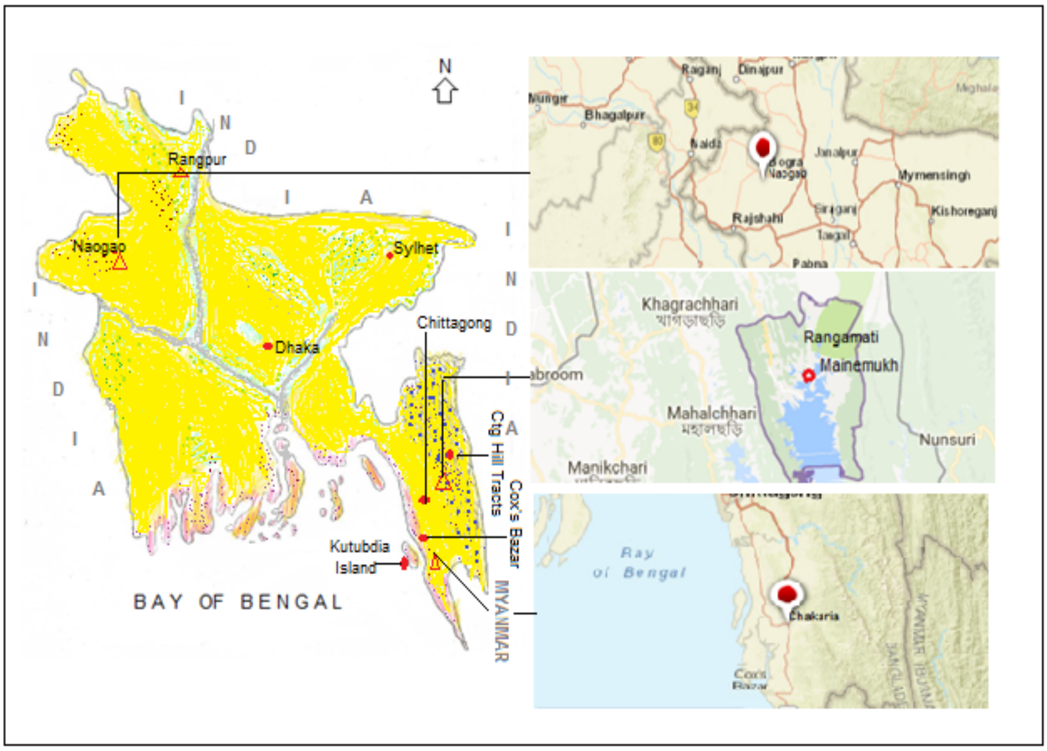


Figure 4.1: Hybrid mini-grid study locations (red triangles)

4.3.1 Hybrid Mini-grid Group 1

Three different locations have been selected as study sites depending on variety of renewable energy resources. These are Cox's Bazar, Rangamati and Rangpur. These study locations can be used as the representative for the rest of the non-electrified areas of the country. Cox's Bazar site is characterized by abundant solar and wind resources, whereas Rangpur has the abundance of biomass (rice husk) and solar radiation. Rangamati is characterized by solar, wind, and some hydro resources. All these selected sites have the similar socio-economic characteristics as the market study areas (i.e., Kutubdia, Gazipur and Feni) described in chapter 3.

For this part of the study it has been assumed that a typical village (or service area) has 200 participating families. Households use electrical equipment with wide variations in power. Based on the data collected during the field study in Bangladesh (Chapter 3; Table 3.9 & 3.9a), estimated average maximum and minimum load demands have been constructed (based on the electrical appliances available in the local market) considering the consumers from all income levels (Table 4.2 & 4.3).

Load	Power (W)	Qty	Total Power (W)	Running Hours	Total (Wh)
Light	11	4	44	5	220
Fan	80	2	160	5	800
TV & Mobile	125	1	125	5	625
Total power for 1 household (W)			329	5	
Total power for 200 household (W)			65800		
Total power in Watt (considering 90% demand)			59,220		
Total Energy Requirement (kWh)			**296.1**		

Table 4.2: Estimated typical maximum load demand for a study area

Load	Power (W)	Qty	Total Power (W)	Running Hours	Total (Wh)
Light	8	3	24	5	120
Fan	40	1	40	5	400
TV & Mobile	80	1	80	5	400
Total power for 1 household (W)			144	5	
Total power for 200 household (W)			28,800		
Total power in Watt (considering 90% demand)			25,920		
Total Energy Requirement (kWh)			**129.6**		

Table 4.3: Estimated minimum typical load demand for a study area

Three different types of hybrid systems of 70kW size have been designed for all different study sites to serve the bigger demand of 296.1kWh/d load (Table 4.2) and 30kW hybrid systems were studied as well at two locations only to serve a smaller load demand of 129.6kWh/d (Table 4.3). These hybrid system combinations are are:

1. 70kW wind-PV hybrid systems at Cox's Bazar
2. 70kW wind-PV hybrid systems at Rangamati
3. 70kW and 60kW rice husk based systems at Rangpur and
4. 30kW wind-PV hybrid systems at Cox's Bazar
5. 30kW micro hydro-PV hybrid system at Rangamati

For the wind-PV-diesel hybrid systems with battery backup in Cox's Bazar and Rangamati, same type of system components were used and costs of the specific models of the components were checked against the generic ones (Table 4.4).

Features	**PV module**	**Wind turbine**	**Battery**	**Converter**
Model	Typical RA*	Tidal 1or 3kW	Hoppecke8 OPzS 800	Typical
Power	1 kW	1 kW / 3kW	Nominal voltage: 2V Nominal capacity:800AI (1.6 kWh)	1 kW
Life time	20 years	20 years	Life through-put 845 kWh	25 years
Price (USD)	1600 USD/kW	3000 /8000 /Turbine	175/Battery	250/kW
Replacement	1200USD/kW	1200 / 6000 /Turbine	150/Battery	200/kW
Maintenance	5 USD/kW	50 USD/Turbine	3 USD/Battery	1 USD/kW

* Standard 1kW model supplied by local producer Rahimafrooz (http://www.rahimafrooz-solar.com)

Table 4.4: Components of the group-1 hybrid systems

For the rice-husk based mini-grid in Rangpur biomass gasification method was followed. The features of the gasifier and the generator have been given below (Table 4.5 & 4.6):

Characteristics	**Value**
Particular Model	OI – 405RHP
Biomass consumption	1.3-1.6 kg/kWh
Gas heat value	4500-5500 kJ/m^3
Gas capacity (maximum)	1200 m3/hr
TAR content	<50 mg/m^3
Gasification efficiency	>70%
Self consumed elec. power	2-4 kW
Water consumption (replace evaporation)	<0.5 Liter/kWh

Table 4.5: Features of the proposed Gasifier for rice husk mini-grid

Features of the proposed generator			
Fuel	Biogas	Speed	15-18000rpm
Output	AC Three Phase	Stroke	4 Stroke
Cooling	Water Cooling	Frequency	50/60HZ

Table 4.6: Features of the generator for Rice husk mini-grid

Location 1: Decentralized hybrid mini-grid in coastal belt, Cox's Bazar: Wind-PV-Diesel with battery backup

Inani village, under Ukhia police station of Cox's Bazar district has been selected as the study location 1. This location has abundance of high wind speed and solar radiation all the year round. Average wind speed in this location is 5.3m/s with the maximum and minimum seasonal variation of 6.7m/s and 4.1m/s respectively (Figure 4.2). The 70kW mini-grid system has been designed considering the estimated load demand of 296kWh serving 200 households, five hours a day (Figure 4.3). At this location 70% of the electricity of the RE (renewable energy) will come from the wind turbines and the 30% from the solar panels. RE power generation share in this case has been decided by the preliminary suitable hybridization analysis by HOMER. This system represents a 68-75% of RE sources (wind-solar) and ensures the scheduled power supply for the consumers.

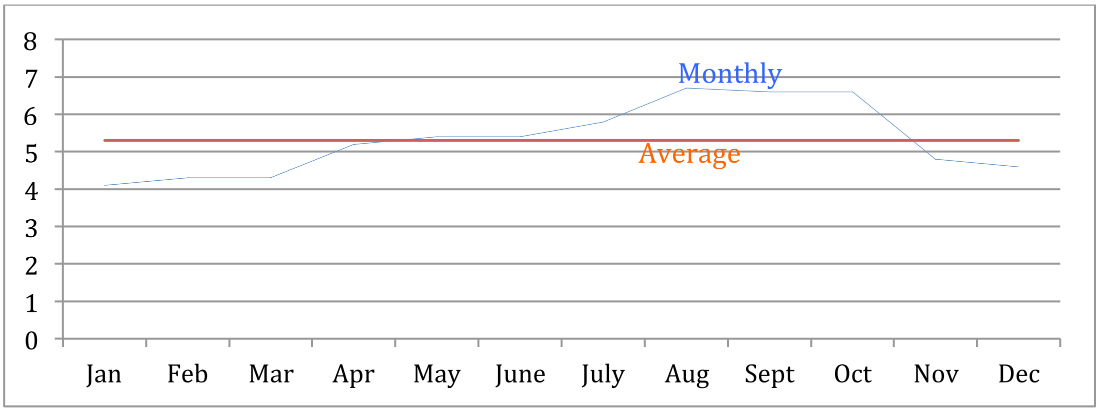


Figure 4.2: Average and monthly wind speed (m/s) at Inani, Ukhia, Cox's Bazar

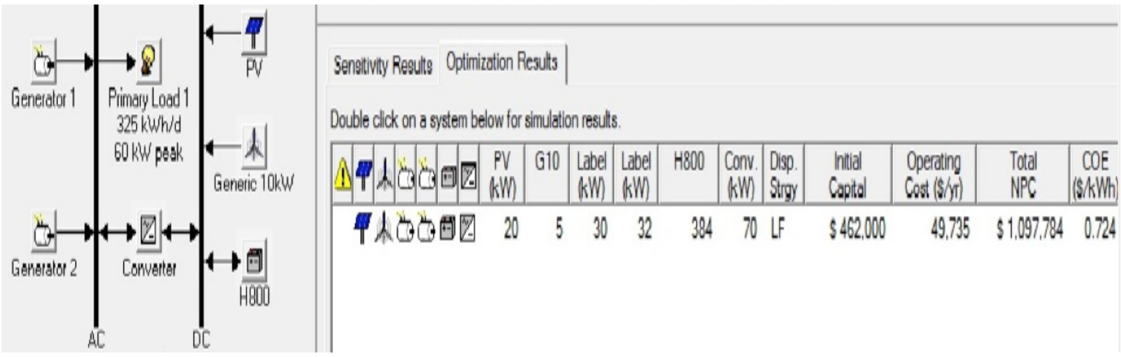


Figure 4.3: Study location-1, Inani village hybrid system architecture and optimization results

To obtain 70% renewable energy from wind turbine, this system had to use 50kW of wind power generation capacity and 20kW of PV. To minimize the cost, five G10 wind turbines (10kW each at a cost of USD 25,000/turbine) were applied instead of either 50 turbines of 1kW each or 17 Turbines of 3kW each. This approach offered huge savings in wind turbine's base construction cost.

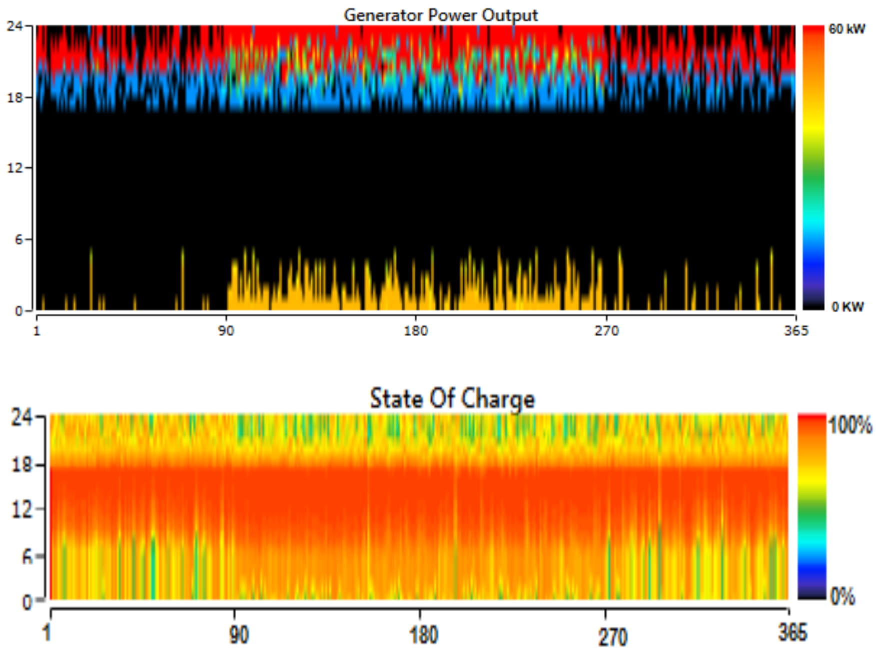


Figure 4.3a: Study location 1, generator output and the battery charge state over the year

This hybrid system combination uses diesel generator regularly to supplement the battery power backup in the late evening hours (Fig 4.3a). HOMER suggested two diesel generators of 30kW capacity each instead of a 60kW capacity one. During the summer months only one generator of 30kW seems efficiently supplying the deficit. On the other hand, having the load following strategy applied battery bank does not apply its full potential during the winter months (November to February) as the wind speed remains relatively lower this time (Fig 4.3a) both of the generators operate to maintain the load demand.

<u>**Location 2:** Decentralized hybrid mini-grid in Rangamati: Wind-Solar-Diesel with battery backup:</u>

A hilly village, Baghaichari in Rangamati district under Chittagong Hill Tracts has been selected as the study Location 2. This region is characterized by the ethnic Chakma dwellers. However, comparing to some other hilly regions this study area is densely populated by the abundance of Bengali settlers. This area is a combination of hill, lake and plain land and is situated at the upstream of the Kaptai Lake, which is the source of the biggest hydroelectric power plant of the country. Unfortunately, Baghaichari village has not been connected to the national grid.

This study area is blessed with potential solar radiation (Figure 4.4). The proposed project is situated at the top of a hill (55m). Wind speed studied here by the LGED is 4.6m/sec on average with a maximum and minimum of 5.8/sec and 4.1m/sec respectively. The hybrid system (70kW) considered here to serve 5 hours of evening load consists of wind turbine, solar PV, battery backup and diesel generator. Considering the lower wind speed compared to the location 1, 'HOMER pro' pre-feasibility study suggested the suitable generation combination of 70% of the power from the solar and the rest 30% from the wind turbine and the generator only to supplement any shortage of power from the renewables (Figure 4.5).

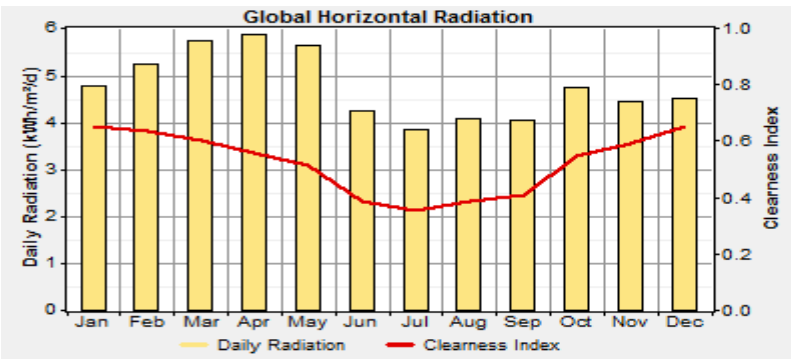


Figure 4.4: Solar radiation profile for Baghaichari (NREL)

PV (kW)	G3	Label (kW)	Label (kW)	H800	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
60	8	65		384	70	LF	$ 567,000	39,709	$ 1,074,617	0.709	0.74	0.00	11,777	774
60	8	65	32	384	70	LF	$ 579,000	39,712	$ 1,086,653	0.717	0.74	0.00	11,685	611
60	8		32	384	70	CC	$ 563,000	44,149	$ 1,127,367	0.767	0.68	0.04	12,494	

Figure 4.5: Study location-2, Baghaichari hybrid system and component optimization results

The optimum hybrid system in this case comprises of 60kW PV, 24kW wind turbine, 384 led acid batteries and a 65kW diesel generator (Fig 4.5). The top ranked system uses 11,700 litres of diesel a year, as the turbines cannot produce enough power with the low wind speed. On average diesel generator runs two hours a day throughout the year.

Location 3: Decentralized mini-grid in Rangpur: Rice Husk based power plant:

Santal, a remote village in Rangpur district has been selected as the study Location-3. It has been assumed that rice husk will be collected for the proposed 70kW power plant from the adjacent rice mills. The annual paddy processing capacity was estimated to be 1.37 million ton per year for the project area in Rangpur and Ahmed and Akhtaruzzaman, (2010) estimated that the 192,551 tons of husk available only for electricity generation in this area. Consumption of rice husk for producing electricity depends on the type of the technology applied. Shing (2007) explored that husk consumption is 1.3 and 1.86 kg for steam turbine and gasification technique respectively. Based on this assumption a 70kW to 100kW power plant can run smoothly on the available husk supply throughout the year.

Two different load scenarios have been studied for this proposed micro-grid system (Figure 4.6). Primary load profile 1 (208kWh/d and 56kW peak) considered only 5 hours of electricity supply for the domestic consumers and rice mills in the evening. In load profile 2 (328kWh/d and 72kW peak), nearby rice mill(s), small businesses and seasonal irrigation activities were added to supply 7 hours of electricity only in day time while serving the domestic loads in the evening.

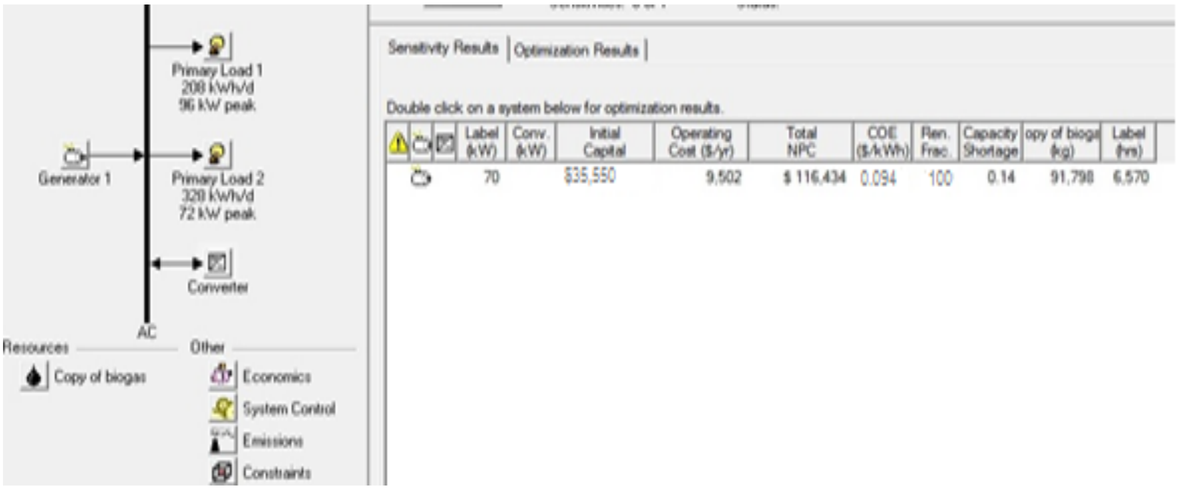


Figure 4.6: Study location-3, Santal village Rice husk mini-grid system architecture and optimization results for load profile 1

Hybrid System	Gasifier	Generator	Initial capital	Operating cost (USD/y)	Total NPC (USD)	COE (USD/kWh)
328kWh/d 72kW peak 12 hours serving	80	60	85,000	12,345	174,567	0.172
208kWh/d 56kW peak 5 hours serving	70	-	35,550	9,052	116,434	0.094
	70	60	75,000	10,546	154,215	0.131

Table 4.6a: Santal village different Rice husk mini-grid system optimization results for load profile 1 & 2

As it is assumed that rice husk supply is available all the time day and night, this system needs no battery storage or backup diesel generator. However, while designing the possible optimal systems for both the load profiles diesel generators were applied as well to assure uninterrupted electricity supply (Table 4.6a). On the other hand, the rice husk system designed without a standby generator for the smaller load offers relatively lower cost of electricity (USD 0.094/kWh).

Location 4: 30kW wind-PV hybrid system at Cox's Bazar

This hybrid system applied two different load profiles (Figure 4.7 & 4.8) to compare the cost of electricity. For load profile 1 (Figure 4.7), the system has been designed to supply electricity only for 5 hours in the evening for the domestic customers (67kWh/d). On the other hand for load profile 2 (Figure 4.8), the hybrid system supplies electricity for 11 hours (107kWh/d). The extra hours cover various business and agricultural activities in the daytime.

Primary Load 1

Scaled annual average:	67.4 kWh/d
Scaled peak load:	29.6 kW
Load factor:	0.0948

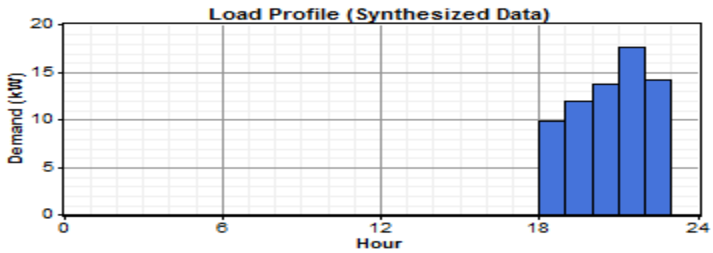


Figure 4.7: Hybrid system characteristics and load profile-1 for Cox's Bazar 30kW Wind-PV mini-grid

Primary Load 2

Scaled annual average:	107 kWh/d
Scaled peak load:	29.7 kW
Load factor:	0.150

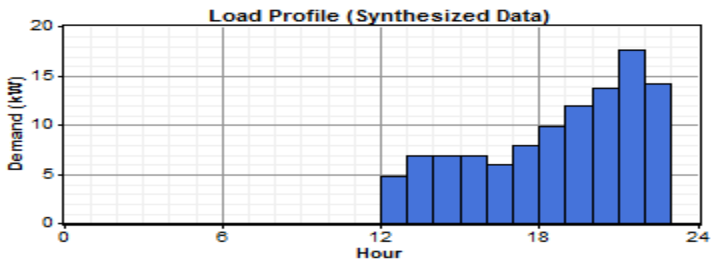


Figure 4.8: Hybrid system characteristics and load profile-2 for Cox's Bazar 30kW Wind-PV system

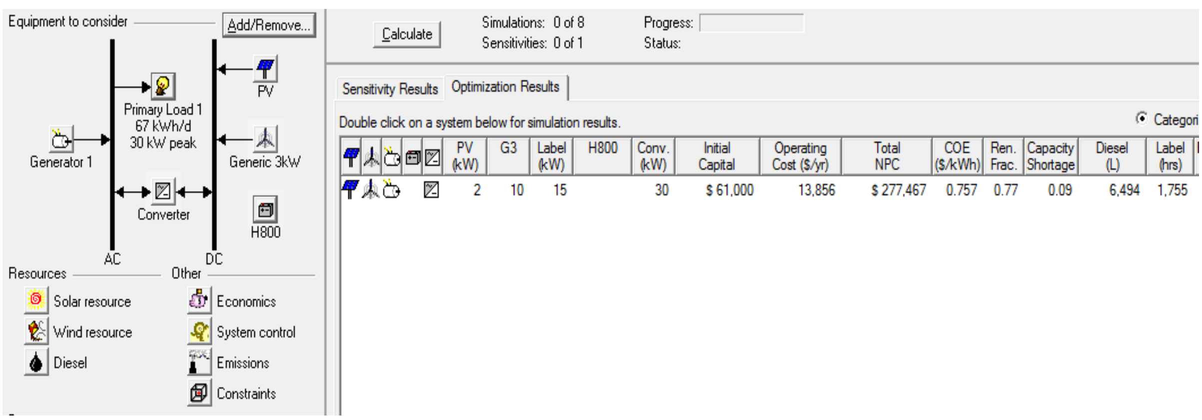


Figure 4.9: Hybrid system architecture and sensitivity analysis for Cox's Bazar 30kW hybrid system (load profile-1)

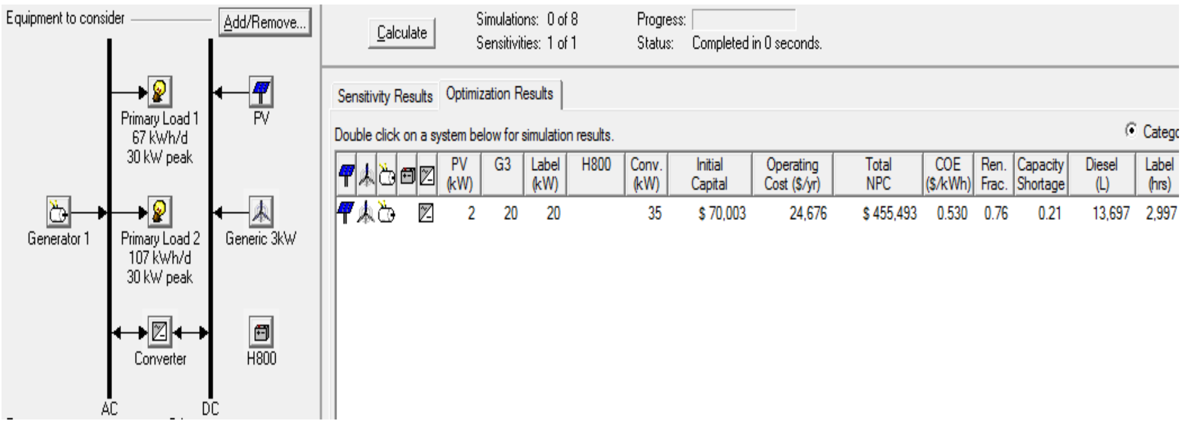


Figure 4.10: Hybrid system architecture sensitivity analysis for Cox's Bazar 30kW hybrid system (load profile-2)

Hybrid systems serving same peak load (30kW) with a larger profile of 107kWh/d for 11 hours offer better optimization outcomes compared to the smaller profile of 67kWh/d for 5 hours and hence produces lower COE (Fig 4.9 & 4.10). Extended hours of demand have been spread over the day times which enables the renewable components to supply the surplus energy to meet the load without using the battery storage and generator.

Location 5: Mainemukh 30kW micro hydro-PV hybrid system

The Mainemukh village having the 'Thankhune Canal' hydro resources in the Rangamati district was selected for the proposed 30kW hybrid system to supply electricity for only 6 hours in the evening. However, another hybrid system serving extended load for 13 hours a day has been designed to compare the system performance and economics. A 40% capital subsidy was applied with the hybrid systems serving both the load profiles. This is the only attempt in applying any capital subsidy for the group-1 hybrid systems.

Water from the Thankhune canal was estimated to supply around 18-20kW of electricity on average. 40kW PV, 30kW diesel generator and 60 batteries as power bank were also used along with the 10kW (5kWx2) micro hydro for the hybrid systems in both cases. The features of the micro-hydro component of the hybrid system are as below (Table 4.7).

Features	Value
Type of turbine	Cross flow
Available water head (average)	
October – February	5.0 - 5.5m
March – September	5.5 - 8.5m
Expected flow	180 – 230 liter/second
Penstock length	65m
Flow control	manual
Estimated power output	5kW each

Table 4.7: Features of the micro hydro unit

Generally, during the dry season electricity generation from the micro hydro should drop because of less water flow and the hybrid system would use the battery bank to supply electricity in the evening (Figure 4.10a). This phenomenon would increase the cost of electricity. To deal with this uncertainty, bigger PV capacity has been used in this hybrid system model to charge the battery bank applying the 'load following' strategy. Moreover the hydro resource has been maintained to produce power in the evening, which reduces the use of battery bank. HOMER preferred a 30kW diesel generator for both load profiles to maintain uninterrupted electricity supply during the peak wintertime when no power might be available from the hydro resource of the Thankhune canal. Different system combinations and sensitivity figures analyzed by HOMER for both the load profiles have been presented in Table 4.8.

Hybrid System	Hydro (kW)	Solar PV (kW)	Diesel Gen. (kW)	Battery	Initial Capital (USD) 0% subsidy *40% subsidy*	Operating Cost/y (USD)	NPC (USD) 0% subsidy *40% subsidy*	COE /kWh (USD) 0% subsidy *40% subsidy*	RE factor (%)
Load 1 32.40kWh/d 6 hours supply	10	40	30	60	74,500 *44,700*	1,321	91,583 *61,783*	0.599 *0.404*	100
Load 2 44.97kWh/d 13hours supply	10	40	30	60	74,500 *44,700*		91,583 *61,783*	0.432 *0.291*	

Table 4.8: Micro hydro-PV hybrid system's sensitivity analysis results by HOMER

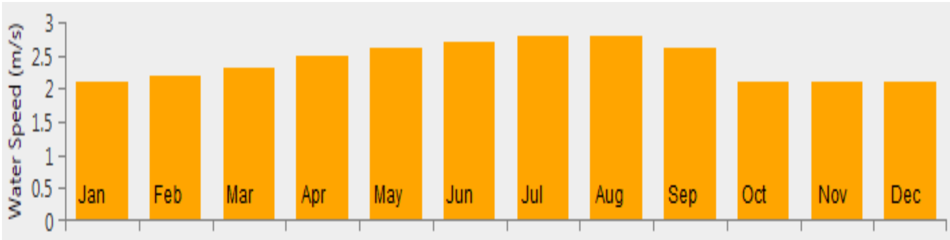
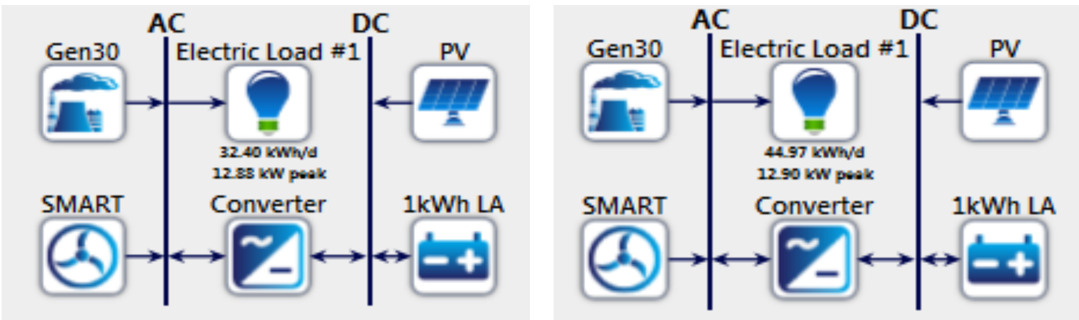


Figure 4.10a: Monthly average water speed

The same hybrid system combinations (Fig. 4.10b) have been designed to serve two different loads of 32.40kW (smaller one) for 6 hours in the evening only and 44.97kW (the bigger wide spread load) for 13 hours (Fig. 4.10c & 4.10g). As the peak demand is almost same (12.88kW and 12.90kW) for the both load profiles (Fig 10.b) hybrid system architecture remains the same (Fig 4.10e, 4.10f, 4.10i & 4.10j).



Schematic A

Schematic B

Figure 4.10b: Hybrid system architectures for 6 hours (schematic A) and extended 13 hours (schematic B) of electricity supply

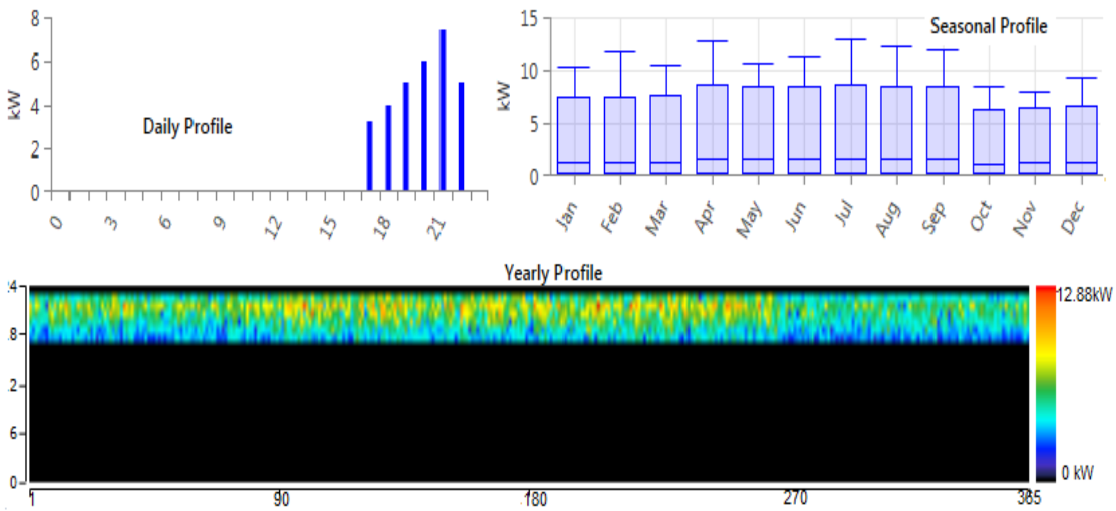


Figure 4.10c: Six hours load profile (Black space in the yearly profile indicates no load requirement)

Both the hybrid systems having the same component combination of 60kW PV, 10kW of hydro, 30kW diesel generator, 20kW converter and 60 batteries are capable of serving the required load demands without using the diesel generator and RE technologies produce same proportion of electricity (Fig. 4.10d & 4.10h).

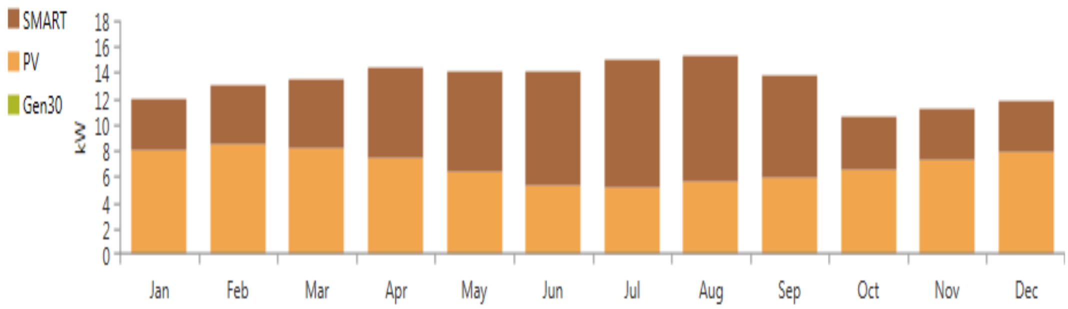


Figure 4.10d: Monthly average electricity production by hybrid system components (six hours load)

Cost of electricity is relatively higher regardless of applicable subsidy (0% to 40%) while the proposed system serves the smaller load (Fig. 4.10e & 4.10f).

Architecture						Cost				System
PV (kW)	Gen30 (kW)	1kWh LA	SMART	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
40.0	30.0	60	2	20.0	LF	$0.599	$91,583	$1,321	$74,500	100

Figure 4.10e: Hybrid system (10% capacity shortage) optimization results for six hours load profile with no capital subsidy

Architecture						Cost				System
PV (kW)	Gen30 (kW)	1kWh LA	SMART	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
40.0	30.0	60	2	20.0	LF	$0.404	$61,783	$1,321	$44,700	100

Figure 4.10f: Hybrid system (10% capacity shortage) optimization results for six hours load profile with 40% capital subsidy

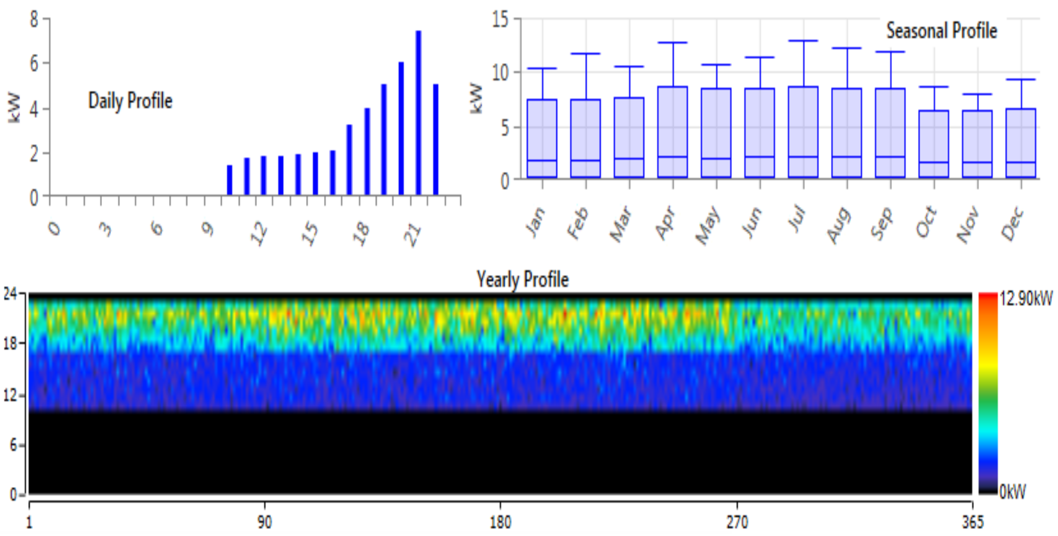


Figure 4.10g: Extended 13 hours load profile (Black space in the yearly profile indicates no load requirement)

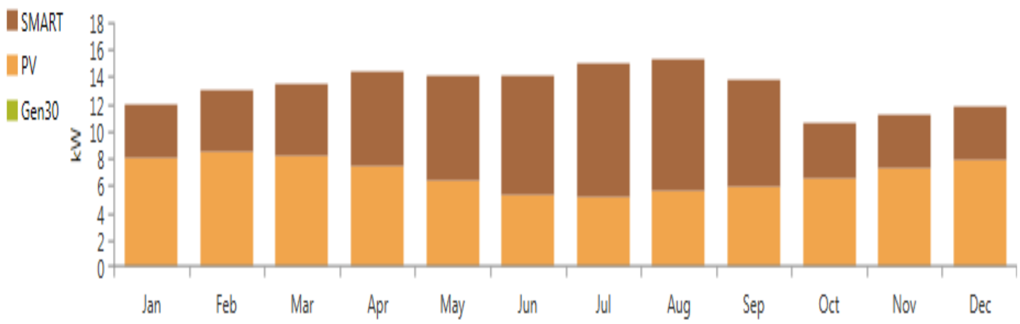


Figure 4.10h: Monthly average electricity production by hybrid system components for extended (13 hours) load profile

Hybrid system's COE drops a lot while serving wide spread load (13 hours). Without any capital subsidy the proposed system can produce electricity for USD 0.432/kWh and with a 40% subsidy cost reduced to USD 0.291/kWh (Fig. 4.10i & 4.10j).

Architecture											Cost				System
					PV (kW)	Gen30 (kW)	1kWh LA	SMART	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
					40.0	30.0	60	2	20.0	LF	$0.432	$91,583	$1,321	$74,500	100

Figure 4.10i: Hybrid system (10% capacity shortage) optimization results for extended (13 hours) load profile with no capital subsidy

Architecture						Cost				System
PV (kW)	Gen30 (kW)	1kWh LA	SMART	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
40.0	30.0	60	2	20.0	LF	$0.291	$61,783	$1,321	$44,700	100

Figure 4.10j: Hybrid system (10% capacity shortage) optimization results for extended (13 hours) load profile with 40% capital subsidy

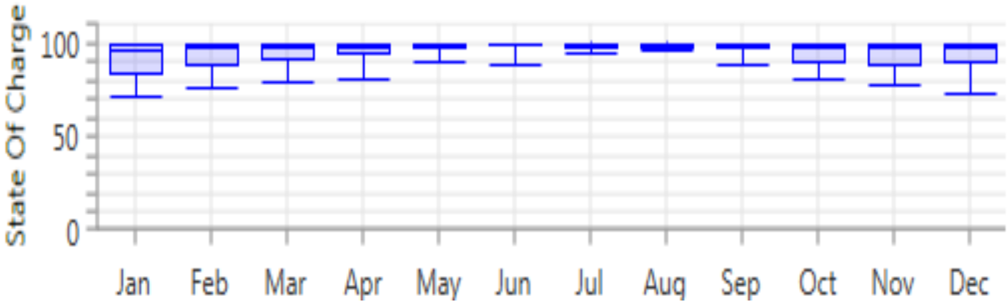


Figure 4.10k: State of battery bank use over the year by the hybrid system serving the extended load

The smart optimization between load demand (in case of wide spread hours) and system architectures reduces the battery bank usages (Fig 4.10k), which in turn reduces the COE.

4.3.1.1 Results for Hybrid Mini-grid Group 1

In the present study it has been evident that serving a particular load in a shorter period (5-6 hours evening load only) all combinations of 'wind-solar-diesel-battery' hybrid systems for a specific given capacity, the cost of electricity remains more or less same and it ranges from USD 0.70kWh to 0.76/kWh (Fig. 4.3 & 4.5). Notably, these mini-grid systems had no capital subsidy. This price range of electricity is very high and beyond consumer's maximum willingness to pay in rural and remote areas (Chapter 3; Table 3.13).

In location-1, while trying to achieve maximum power delivery from the wind turbine(s) (50kW wind and 20kW PV) the battery bank has been designed to be charged through load following (LF) strategy both by the wind and solar components. As the electricity demand is only concentrated in a short space of evening hours, stored power in the battery bank exhausts quickly and the balance of the load is served *in situ* by the diesel generator(s). The heavy fuel and battery dependency of this hybrid system (Figure 4.3a) makes it economically unattractive. The same types of performance and result have been observed for the location-2 hybrid system (Figure 4.5).

The cost of electricity produced from rice husk at the location-3 in Rangpur found to be the lowest (UDS 0.094/kWh) for the load profile-1 (small domestic load) compared to other hybrid systems (Fig. 4.6 and Table 4.6a). This is due to the less expensive equipment and installations compared to other renewable systems. Moreover, neither any expensive battery bank nor prolonged diesel generator needs to be used here. However, while a standby generator is added to the hybrid system COE increases to USD 0.131 to 0.172/kWh for (Table 4.6a). For location 1 & 2, the 60kW & 70kW Wind-PV-Diesel hybrid systems capital investment ranges from USD 462,000 to 579,000 (Fig. 4.3 & 4.5) whereas, for the same size (70kW) of rice husk hybrid system capital investment varies between only USD 35,550 (without diesel generator backup) and USD 75,000 (with diesel generator backup) (Fig. 4.6 and Table 4.6a). Higher capital investment turns into higher cost of electricity produced for those hybrid systems.

The 30kW Wind-PV hybrid system in Cox's Bazar (Location 4) involves relatively much lower capital investment around USD 60-70,000 (Fig. 4.9 & 4.10). However, cost of electricity is higher (USD 0.75/kWh) for load profile 1, where the system supplies electricity only for 5 hours in the evening through the battery bank (Fig. 4.9). This cost reduced to USD 0.53/kWh (Fig. 4.10) for load profile 2, where the system supplies electricity for extra 6 hours in the day time with minimal battery backup as the wind turbine supplies some electricity during the evening hours.

In this location-5, the Mainemukh 30kW micro hydro-PV hybrid systems use the same combination and sizing of components (10kW hydro, 40kW solar, 30kW generator and 60 kW battery bank) for serving two different load profiles (Table 4.8; Fig. 4.10c & 4.10g). COE varies between USD 0.599 to 0.432/kWh for the smaller load (32.40kWh/d over 6 hours only in the evening) and the bigger load (44.97kWh/day over 13 hours) considering no capital subsidy (Fig. 4.10e & 4.10i).

Applying a 40% capital subsidy system can produce electricity USD 0.404/kWh and USD 0.291/kWh (Table 4.8; Fig. 4.10f & 4.10j). Potential water resource (Fig. 4.10a) makes this site suitable for micro-hydro-PV hybrid mini-grid to supply electricity in this remote off-grid area. System combinations kept similar for two different load profiles, as the peak demands remain the same (Fig. 4.10b). In both cases power generation by the RE components are same (Fig. 4.10d & 4.10h).

This group of hybrid mini-grid study included 10% interest on the capital investment and considered no capital subsidy (excluding location-5). It has been observed in location-5 for the extended electricity using hours during the daytime by utilizing maximum renewable fraction and using capital subsidies from the government the cost of electricity can be reduced to a great extent. These phenomena of wide spread load profile, using maximum RE fraction and applying government's policy approved capital subsidy have been applied and analyzed in the group-2 hybrid mini-grids to have more clear insight.

4.3.2 Hybrid Mini-grid Group 2

It has been observed in mini-grid group-1 studies that PV-Wind-Diesel-battery combinations with no capital subsidies COE remains higher than the customers' willingness to pay. However, rice husk and PV-micro hydro mini-grid systems have been exceptional in this case offering much reduced cost of electricity, as the initial investments are much lower than the earlier combinations. The reality of rice husk and micro-hydro resources being limited to only few locations of the country (Chapter 2; Figure 2.8), triggers the need for a different approach of mini-grid design to deal with the PV-Wind-Diesel-battery combinations. It has been shown in previous part of this study (Fig. 4.3 & 4.5) that for the 60-70kW PV-wind-diesel systems at three different locations supplying electricity for 5–6 hours in the evening only, cost of electricity ranges from USD 0.70/kWh to 0.76/kWh considering no capital subsidy and higher interest rate of 10% on capital investment. Simultaneously it was evident that with a 40% capital subsidy in combination with extended hours of project operation could reduce the levelized cost of electricity to a greater extent (Fig. 4.10f & 4.10j). Based on these findings it has been realized that different levels of capital subsidies, interest rate and system working hours need to be applied and studied. Therefore, in group-2, some 80kW PV-Wind-Diesel mini-grids have been designed for Chakaria in Cox's Bazar and Naogao to serve a wider load of 366kWh/d (based on the actual field load demand data). Unlike group-1, these hybrid systems were applied with different levels of subsidies (25% to 40% as stated in government's renewable energy policy) and lower interest rates. The most suitable hybrid systems suggested by HOMER representing multiple optimizations and sensitivity outputs have been presented in detail to have better insights toward suitable business models.

To apply different capital subsidies in the HOMER simulation process, two different approaches were followed.

Approach 1: Deducting the value of subsidy as fixed capital costs (i.e. land, structure, distribution network etc.) from the total project cost. For example, to apply a 25.9% capital subsidy (which is UDS100,000) on a USD 386,000 project fixed capital cost has been applied as zero (ø) and initial capital cost as USD 286,000 for the Naogao hybrid system (Fig. 4.11; 4.12 & 4.13). This approach complies with the governments' policy of subsidizing fixed capital cost of decentralized hybrid renewable energy generating projects (BPDB, 2008).

Approach 2: Applying cost multiplier into HOMER component cost input as well as in to the estimated capital cost of the hybrid system. For example, in previous section (4.3.1; Location 5), 40% capital subsidies were applied in different hybrid systems using 0.60 as constant cost multiplier (Fig. 4.10f & 4.10j) and for PV-Wind-diesel hybrid systems, Naogao in mini-grid group-2 (Fig. 4.19b & 4.19d).

For the 80kW Naogao hybrid systems (90kW PV, 4x10kW wind turbine, 60kW diesel generator and battery backup), assuming 26% capital subsidy (covering the fixed capital cost, i.e, land lease, building, distribution network etc.) levilized cost of electricity (LCOE) estimated as USD 0.273/kWh, 0.289/kWh and 0.354/kWh while interest rates calculated at 5%, 6% and 10% respectively (Fig. 4.11; 4.12 & 4.13).

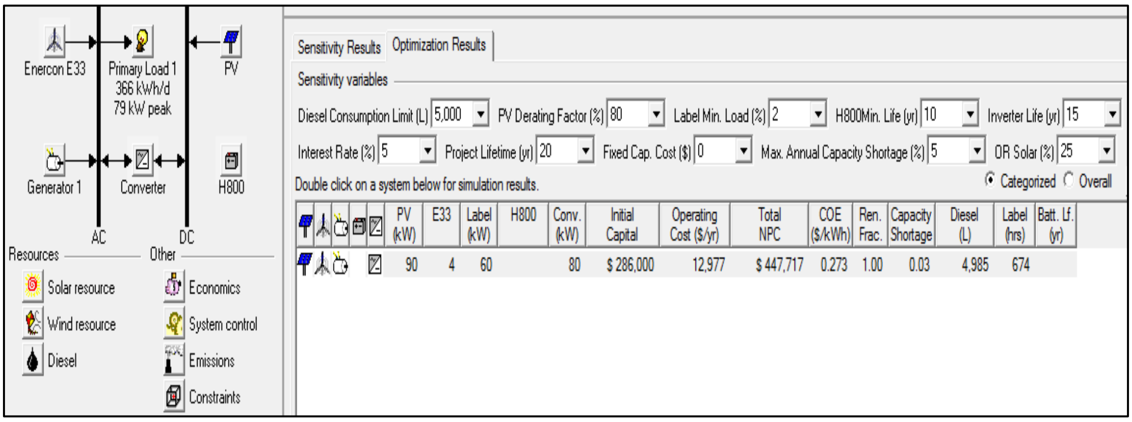


Figure 4.11: Naogao Wind-PV-diesel hybrid system optimisation results 1 (26% capital subsidy, 5% interest)

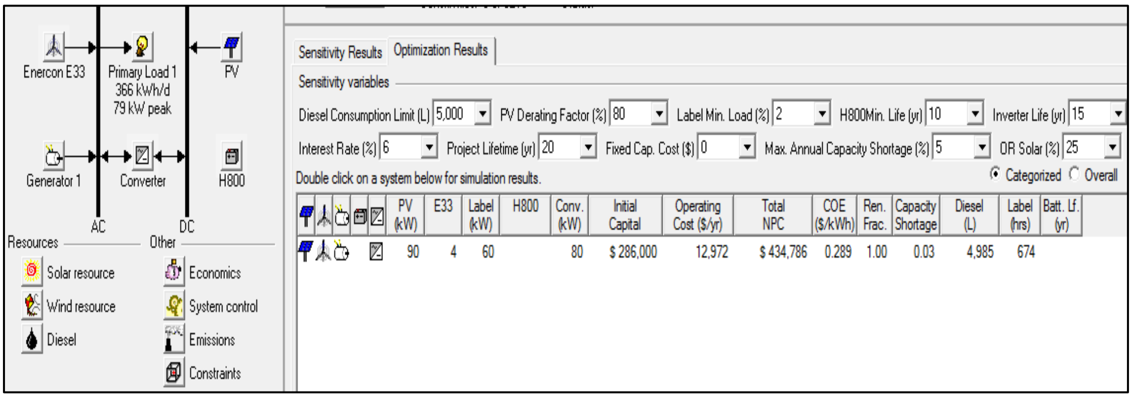


Figure 4.12: Naogao Wind-PV-diesel hybrid system optimisation results 2 (26% capital subsidy, 6% interest)

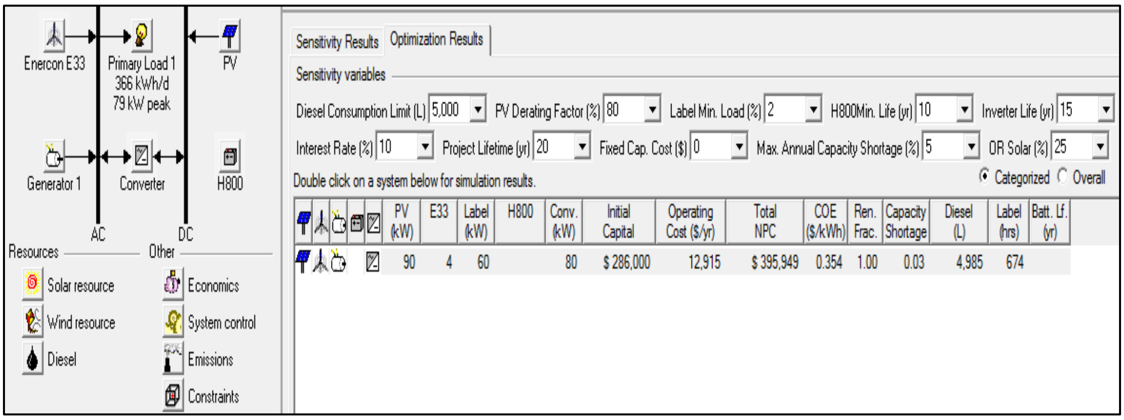


Figure 4.13: Naogao Wind-PV-diesel hybrid system optimization results 3 (26% capital subsidy, 10% interest)

However, for the same system configuration (90kW PV, 4x10kW wind turbine, 60kW diesel generator and battery back up), assuming no capital subsidy LCOE estimated as

USD 0.335/kWh, 0.355/kWh and 0.443/kWh while interest rates calculated at 5%, 6% and 10% accordingly (Fig. 4.14; 4.15 & 4.16).

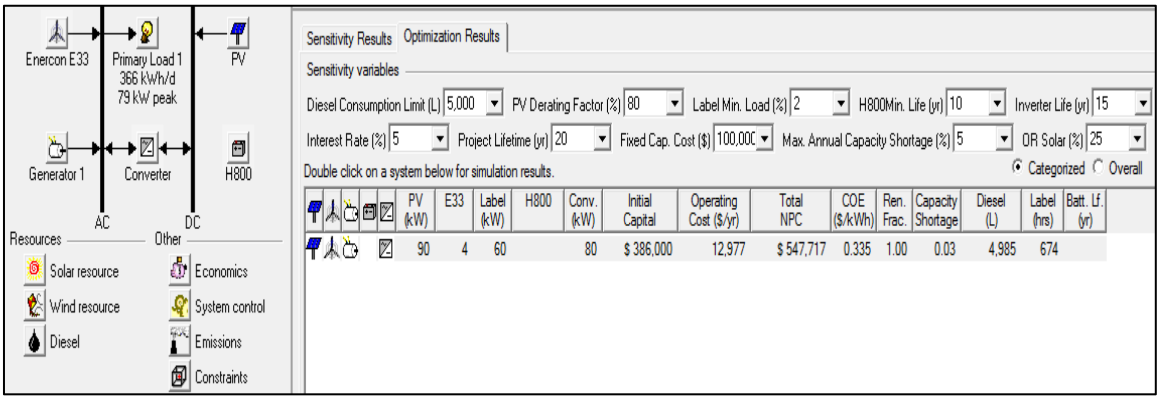


Figure 4.14: Naogao Wind-PV-diesel hybrid system optimisation results 4 (no capital subsidy, 5% interest)

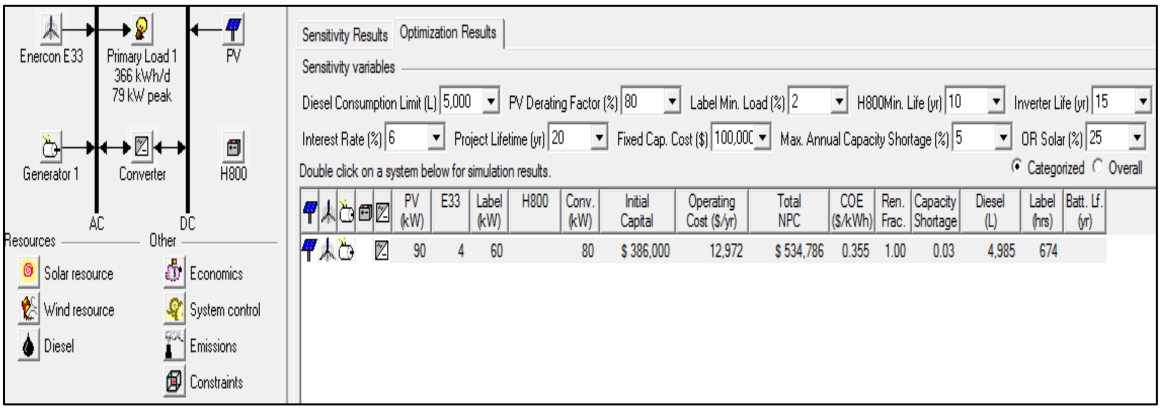


Figure 4.15: Naogao Wind-PV-diesel hybrid system optimisation results 5 (no capital subsidy, 6% interest)

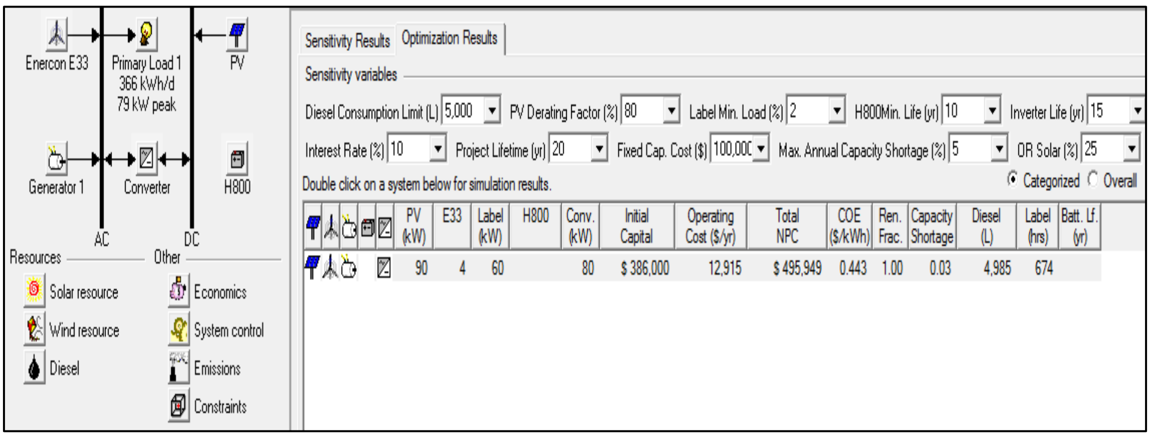


Figure 4.16: Naogao Wind-PV-diesel hybrid system optimisation results 6 (no capital subsidy, 10% interest)

For the 80kW Chakaria PV-Wind-diesel hybrid system (60kW PV, 10x3.5kW wind, 60 kW diesel generator and battery backup) with no capital subsidy LCOE estimated as USD 0.262/kwh, 0.275/kWh and 0.339/kWh while assuming 5%, 6% and 10% interest rate on the capital investment respectively (Fig. 4.17; 4.18 & 4.19).

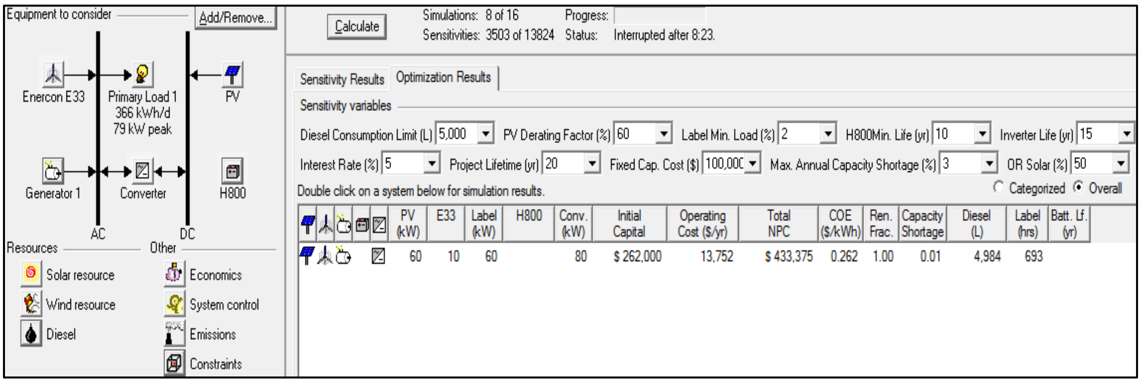


Figure 4.17: System optimization results 7 (no capital subsidy)

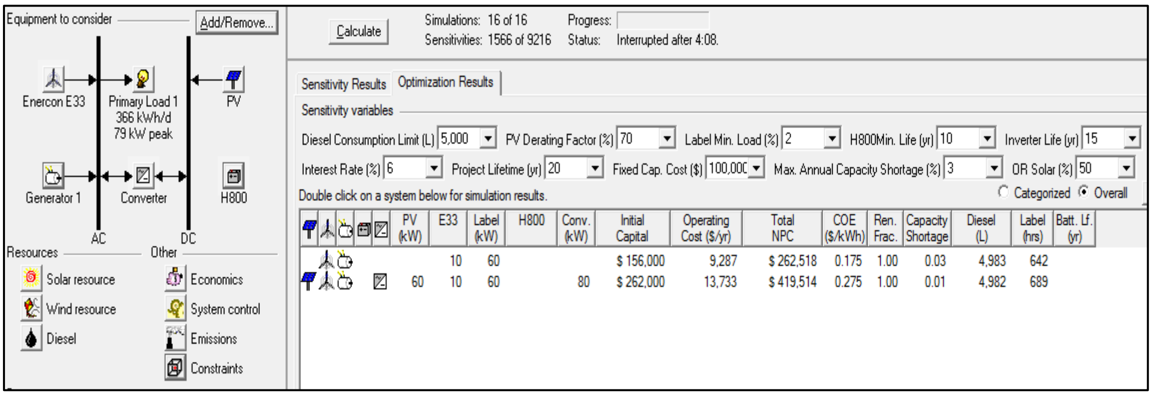


Figure 4.18: System optimization results 8 (no capital subsidy)

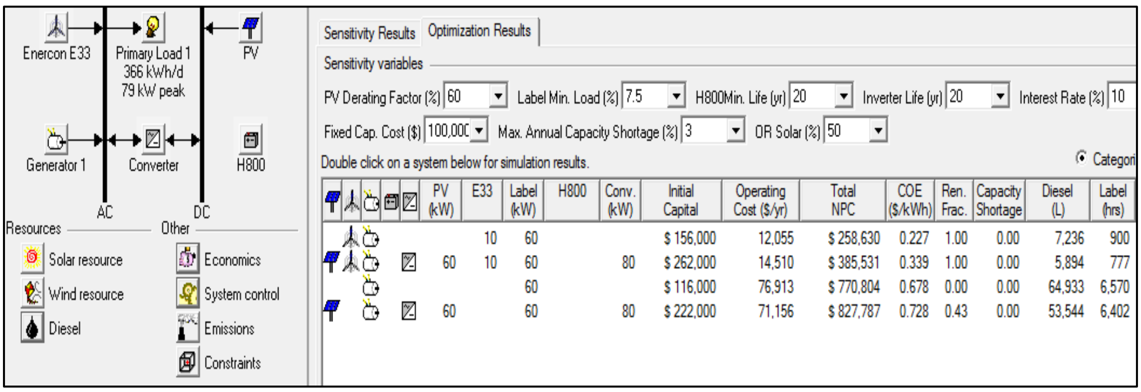


Figure 4.19: System optimization results 9 (no capital subsidy)

Finally, hybrid systems for Naogao (PV-diesel-battery) without any wind turbine were designed and analyzed to be the representative models for other areas of the country where there is no potential wind power available. PV-diesel-battery hybrid systems were analyzed to serve two different load profiles (*profile 1: 299kWh/d, 97.36kW peak, serving duration 6 hours and profile 2: 366kWh/d, 80.46kW peak, serving duration 12 hours*). The optimized system architecture suggested by HOMER was a combination of 140kW PV, 40kW generator, 80kW converter and storage of 440 batteries. The optimization results related to different load profiles and economic characteristics have been presented below (Figure 4.19a to 4.19d). These systems were applied with 6% interest on initial investment.

Architecture						Cost				System
PV (kW)	Gen50 (kW)	1kWh LA	Converter (kW)	Dispatch		COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
140	40.0	440	80.0	LF		$0.439	$526,124	$29,285	$187,000	70

Figure 4.19a: Naogao Solar PV-diesel hybrid system (for load profile 1, no capital subsidy) optimization results

Architecture						Cost				System
PV (kW)	Gen50 (kW)	1kWh LA	Converter (kW)	Dispatch		COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
140	40.0	440	80.0	LF		$0.377	$451,324	$29,285	$112,200	70

Figure 4.19b: Naogao Solar PV-diesel hybrid system (for load profile 1, 40% capital subsidy) optimization results

Architecture						Cost				System
PV (kW)	Gen50 (kW)	1kWh LA	Converter (kW)	Dispatch		COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
140	40.0	440	80.0	LF		$0.357	$543,830	$29,087	$207,000	77

Figure 4.19c: Naogao Solar PV-diesel hybrid system (for load profile 2, no capital subsidy) optimization results

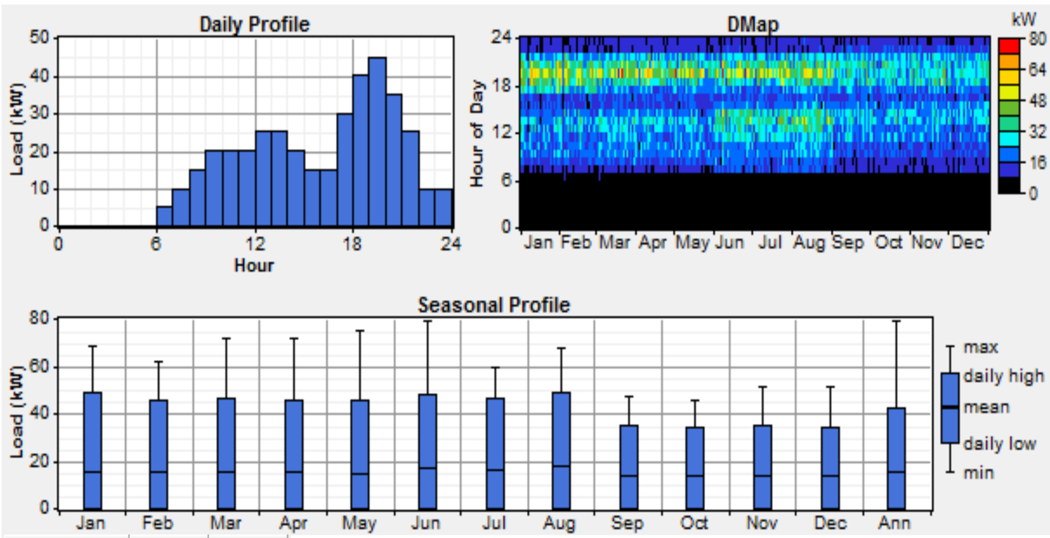
Architecture									Cost				System
				PV (kW)	Gen50 (kW)	1kWh LA	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
				140	40.0	440	80.0	LF	$0.308	$469,030	$29,087	$132,200	77

Figure 4.19d: Naogao Solar PV-diesel hybrid system (for load profile 2, 40% capital subsidy) optimization results

Hybrid system performs better while serving wide spread load over longer hours having relatively lower peak load demand (Figure 4.19c & 4.19d).

4.3.2.1 Results for Hybrid Mini-grid Group 2

Better LCOE have been achieved in the Naogao and Chakaria Wind-PV-diesel hybrid systems for their wide spread load profiles (Fig. 4.20) supplying electricity for 18 hours a day in comparison to the very limited usages of electricity (5 to 7 hours a day) in the previous part of this study (Fig. 4.7 & 4.8).



	Baseline	Scaled
Average (kWh/d)	366	366
Average (kW)	15.3	15.3
Peak (kW)	78.9	78.8
Load factor	0.193	0.193

Figure 4.20: Load profile for the Chakaria and Naogao 80kW hybrid mini-grids

In the sensitivity analysis, Naogao 80kW hybrid system with a 5% interest on capital represents LCOE varying from USD 0.248/kWh to USD 0.336/kWh with analyzed net present cost (NPC) of USD 401,120 and USD 548,573 for 40% capital subsidy and no subsidy at all respectively (Table 4.9). On the other hand the Chakaria 80kW hybrid system offers LCOE as USD 0.217/kWh with 40% capital subsidy and 5% interest on capital. In this case the NPC turns as USD 332,000 for the hybrid system. A 5% increase on the capital interest (which is 10%) while applying 40% capital subsidy LCOE increases to USD 0.313 to USD 0.245/kWh for the same Naogao and Chakaria hybrid system. Therefore, a relatively lower interest rate (5%) is preferred although applying a fixed capital cost subsidy (40%) to keep the cost of electricity at a reasonable level.

Project	Maximum capacity shortage	Capital Subsidy USD	Capital Subsidy (%)	Investor's Capital USD	Total Capital USD	Interest Rate (%)	Project life (Year)	Battery Life (Year)	Operating Cost/year UDS	NPC USD	COE USD/kWh
Naogao 80kW Hybrid System	5%	100,000	25.90	286,000	386,000	5	20	10	12,977	447,717	0.273
	5%	0	0	386,000	386,000	5	20	10	13,045	548,573	0.336
	5%	155,000	40.16	231,000	386,000	5	20	10	13,166	401,120	0.248
	5%	100,000	25.9	286,000	386,000	6	20	10	12,972	434,786	0.289
	5%	0	0	386,000	386,000	6	20	10	13,040	535,569	0.357
	5%	155,000	40.16	231,000	386,000	6	20	10	13,241	394,316	0.251
	5%	100,000	25.09	286,000	386,000	10	20	10	12,915	395,949	0.354
	5%	0	0	386,000	386,000	10	20	10	12,982	496,520	0.445
		155,000	40.1	231,000	386,000	10	20	10	13,123	354,358	0.313
Chakaria 80kW Hybrid System	5%	100,000	38.17	162,000	262,000	5	20	10	13,641	332,000	0.217
	5%	0	0	262,000	262,000	5	20	10	13,399	415,690	0.271
	5%	65,000	24.8	197,000	262,000	5	20	10	13,531	298,310	0.224
	5%	100,00	38.17	162,000	262,000	6	20	10	12,164	265,562	0.237
	5%	0	0	262,000	262,000	6	20	10	12,084	412,592	0.250
	5%	65,000	24.8	197,000	262,000	6	20	10	11,993	237,412	0.243
	5%	100,000	38.17	162,000	262,000	10	20	10	13,611	277,881	0.245
	5%	0	0	262,000	262,000	10	20	10	13,400	428,997	0.258
	5%	65,000	24.8	197,00	262,000	10	20	10	13,105	243,947	0.249

Table 4.9: Table representing summary of Sensitivity analysis

To obtain the optimal system configurations, technical and economic aspects, a range of key sensitivity variables have been used in this study as below (Table 4.10):

Features	Value
PV derating factor:	60% 70% and 80%
Maximum annual capacity shortage:	2% 3% and 5%
Fuel consumption limit:	3000L/y and 5000L/y
Interest rate:	5% 6% and 10%
Capital subsidy:	24.8% 25.9% 38.2% and 40.2%

Table 4.10: Sensitivity variables for the optimal hybrid systems

HOMER suggests the optimal system configurations with 80% PV derating, 5% maximum capacity shortage, 5000 litre diesel consumption limit, 5% interest on capital and 40.2% capital subsidy (Table 4.9 and Figure 4.21 – 4.24).

For a specific hybrid system (*Max. diesel consumption 5000L; PV derating factor 80%; Label min. load 2%; Battery life 10yrs; Converter life 15yrs; Interest rate 5-10%; Project lifetime 20yrs; Fixed capital cost USD 100,000; Maximum annual capacity shortage 5%; OR solar 25*) study shows a positive correlation between the COE and interest rate, where electricity cost increases with the increase in interest rate Figure (4.21 & 4.22). On the other hand a negative correlation is evident between the total NPC and the interest rate, where total NPC is low with a higher interest rate (Figure 4.23 & 4.24). Cost of electricity reduces with the capital subsidy applied. Better NPC achieved by applying lower interest rate (5%) and higher capital subsidy (41.2%) (Table 4.9 and Figure 4.23 & 4.24).

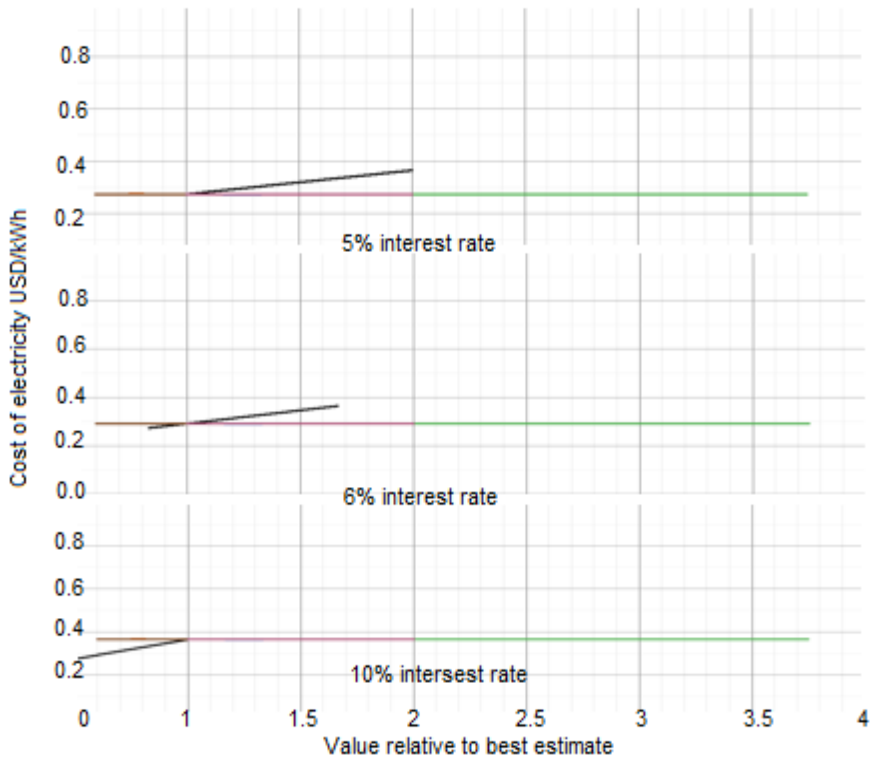


Figure 4.21: Levelized cost of electricity with 5%, 6% & 10% interest rate and 40% subsidy

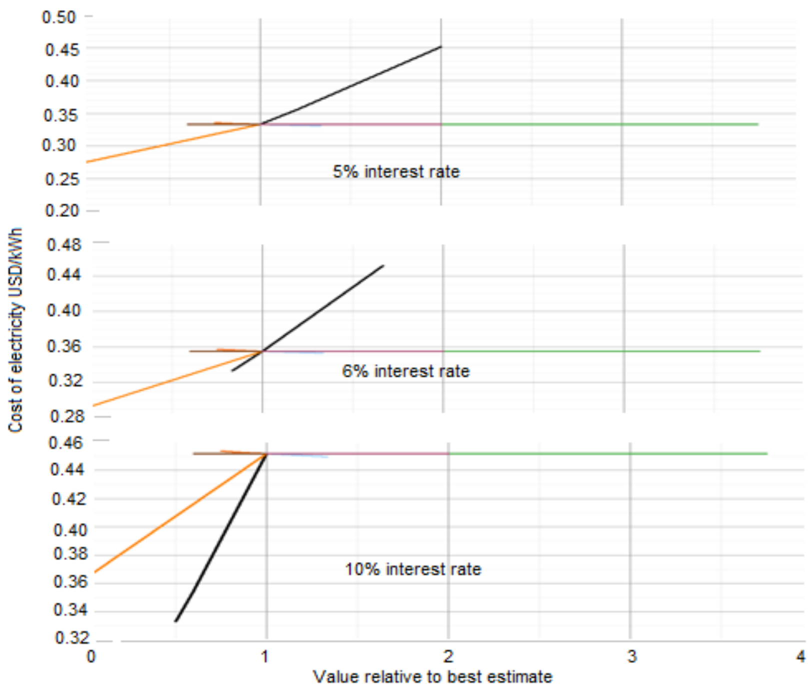


Figure 4.22: Levelized cost of electricity with 5%, 6% & 10% interest rate and no capital subsidy

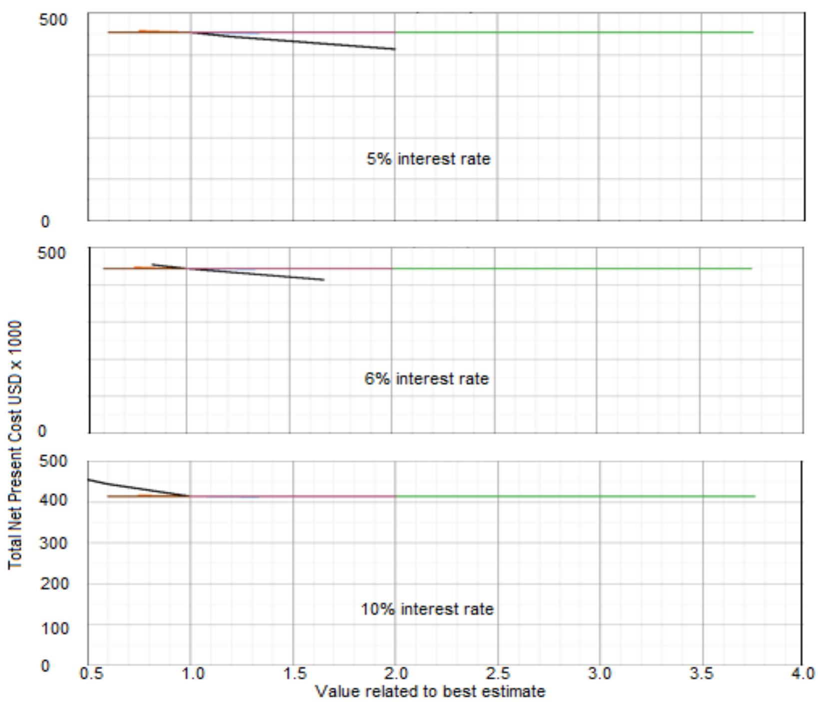
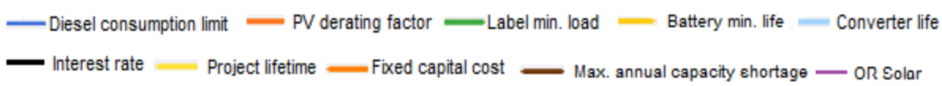


Figure 4.23: NPC with 5%, 6% & 10% interest rate and 40% subsidy



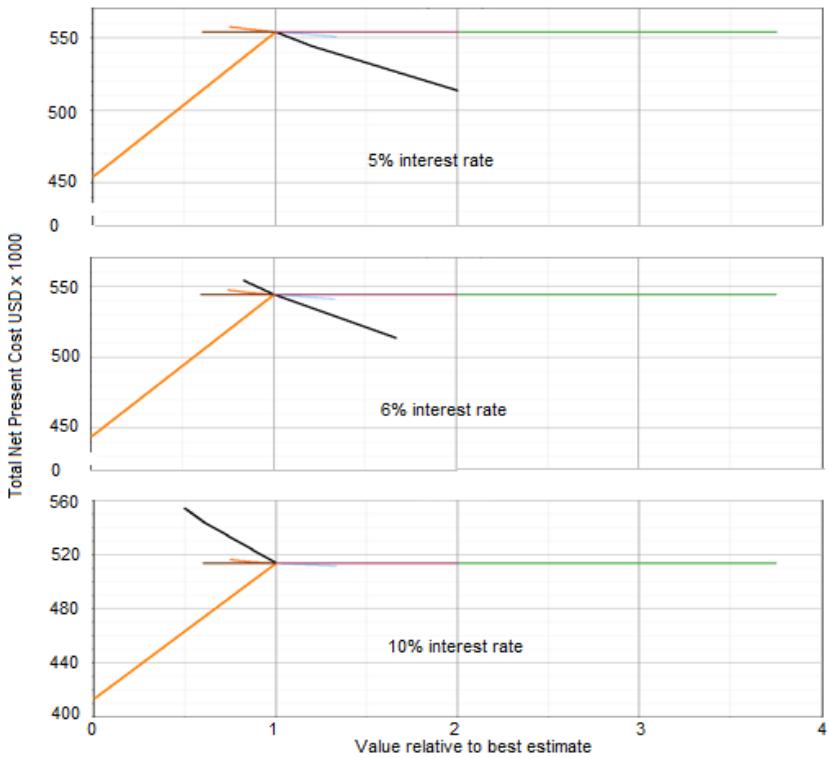
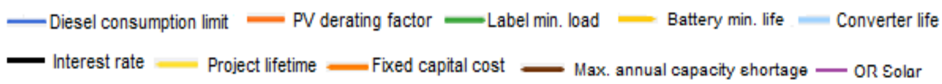


Figure 4.24: NPC with 5%, 6% & 10% interest rate and no subsidy



HOMER suggests the best NPC, USD 401,120 and USD 332,000 for the Naogao and Chakaria PV-Wind-diesel hybrid systems with the lowest interest rate of 5% in both cases and highest capital subsidy of 40% and 38% respectively.

Analyzing results from the Naogao optimum PV-Diesel-Battery hybrid systems, COE observed to vary between USD 0.439/kWh to USD 0.357/kWh applying no capital subsidy for load profile 1 and 2 respectively (Fig. 4.19a & 4.19c). While applied with 40% capital subsidy COE drops between USD 0.377/kWh and USD 0.308/kWh for load profile 1 and 2 respectively (Fig. 4.19b & 4.19.d). HOMER calculated the NPC for the least cost electricity generating hybrid system as USD 469,030 (Fig. 4.19d).

So far, some potential hybrid mini-grid systems have been explored in group-1 and group-2 and these mini-grids are further analysed and discussed later in this chapter.

4.3.3 Hybrid Mini-grid Group 3

In this group of hybrid mini-grids the least electrified areas of the country, coastal non-electrified villages and remote islands have been considered to supply with longer hours of electricity produced from the renewable resources. To suggest the most sustainable techno-economic hybrid mini-grid models for the coastal regions including the islands, ten different system configurations having different load scenarios (built from field data, Chapter-3) have been designed and analysed accordingly. All of these hybrid system models are briefly described initially and two optimal models are discussed elaborately and their results are analysed further in detail.

To get a clear insight into the suitable electricity load profile for the most sustainable hybrid micro-grid implementation three different load profiles were adopted based on the field data (Chapter 3) in this case. These are domestic, combined and managed load profiles. Domestic and combined load profiles were built on the usual life styles of the people in the study areas, i.e. domestic consumers charge mobile phones and play audio devices in the morning, shops run live TVs only in evening and farmers use irrigation pumps in the morning. The managed load profile is based on the assumption that if consumers are permitted to make informed decision on the consumption schedule of electricity, the load demand can be synchronized with the power production schedule of different components of the hybrid systems. For example, shops can run recorded TV for extended hours and farmers can use pumps only when systems produce excess power based on the natural resource supply. *Managed* load profile has been designed to achieve best hybrid system efficiency.

The proposed study areas (Kutubdia Island, Chakaria coastal belt and Sandwip Island) have good wind and solar resources potential (Figure 4.25 & 4.26) to support decentralized renewable electricity production in a sustainable manner.

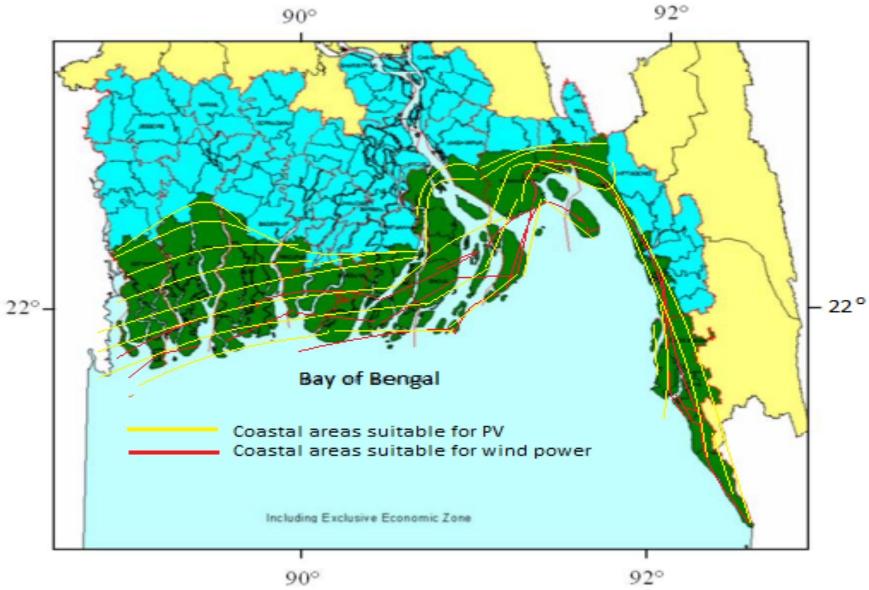


Figure 4.25: Coastal region of Bangladesh (green colour areas) showing PV and wind power potential areas (Alam and Bhattacharyya, 2016)

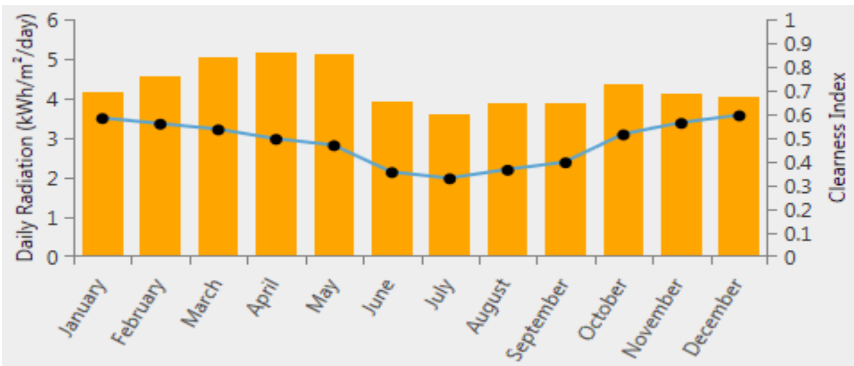


Figure 4.26: Monthly average solar radiation in the study areas (NREL)

Three bigger load profiles applied to serve various combinations of 200 households (including all income group; Chapter 3, Table 3.2), 10 businesses, 5 irrigation pumps and 2 cottage factories for 12 hours (Fig. 4.27) and 16 hours (Fig.4.28 & 4.29) a day termed as ‘Load profile 1, 2 and 3’. On the other hand, two smaller load profiles for two different durations and load patterns serving 6 hours domestic load only (Fig. 4.30) and 15 hours combined domestic and commercial load (Fig. 4.31) termed as ‘Load profile 4 and 5’ were applied to this study. Seasonal domestic, commercial and agricultural or other small industrial loads have been separated for the three bigger load profiles (load profile 1, 2 and 3) to ensure better simulation efficiency (Table 4.11 & 4.12).

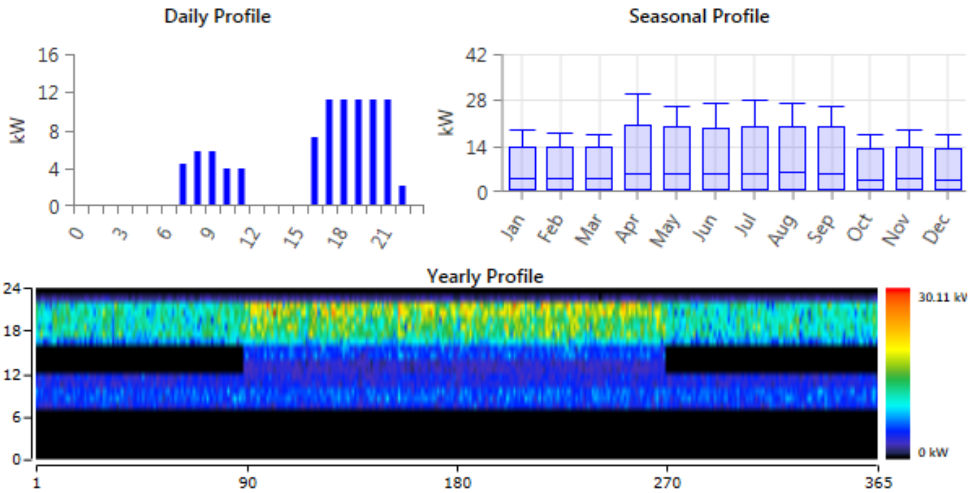


Figure 4.27: Domestic 12 hrs load pattern (load profile 1)

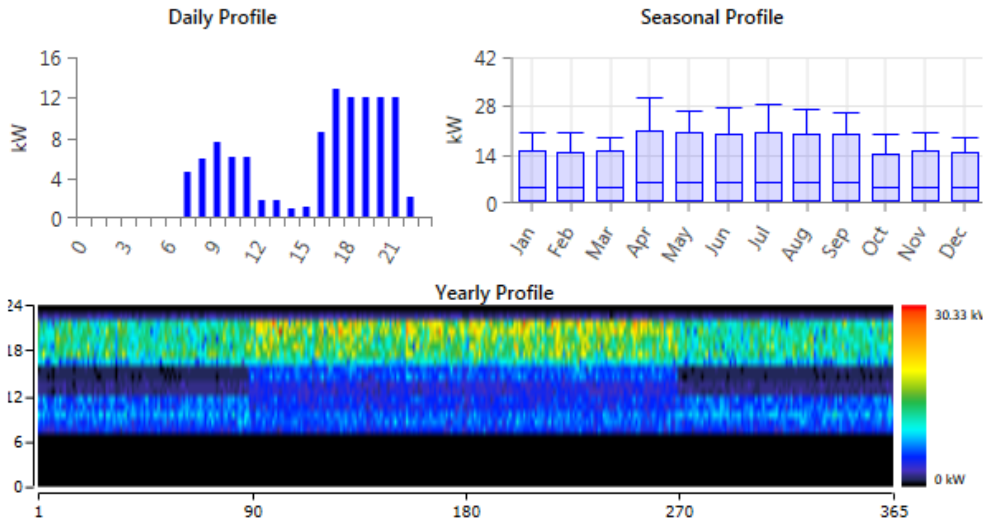


Figure 4.28: Domestic and commercial combined 16 hrs load pattern (load profile 2)

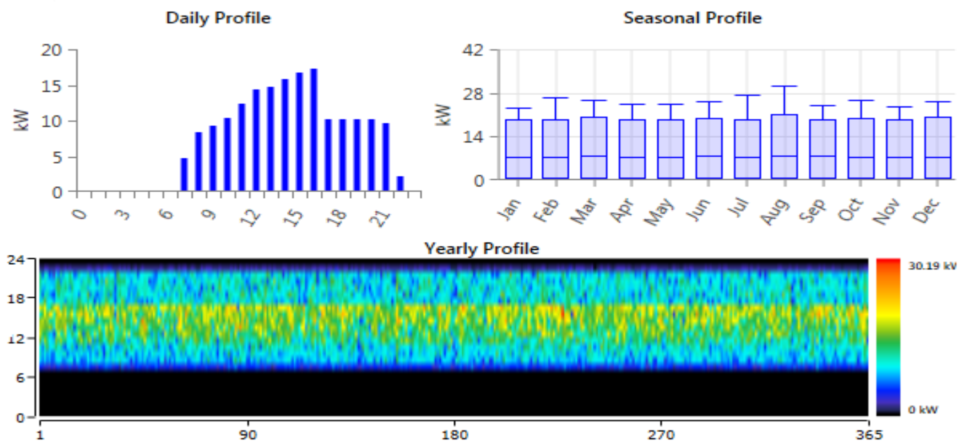


Figure 4.29: Domestic, commercial and agricultural/ industrial managed 16 hrs load pattern (load profile 3)

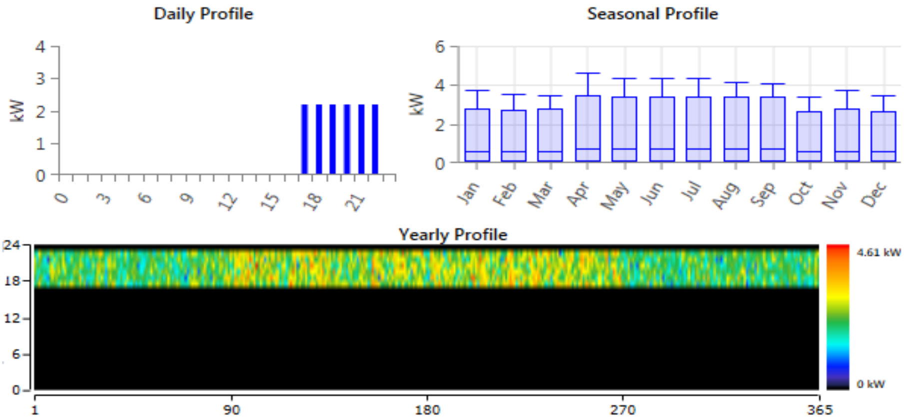


Figure 4.30: Smaller 6 hrs load pattern (load profile 1)

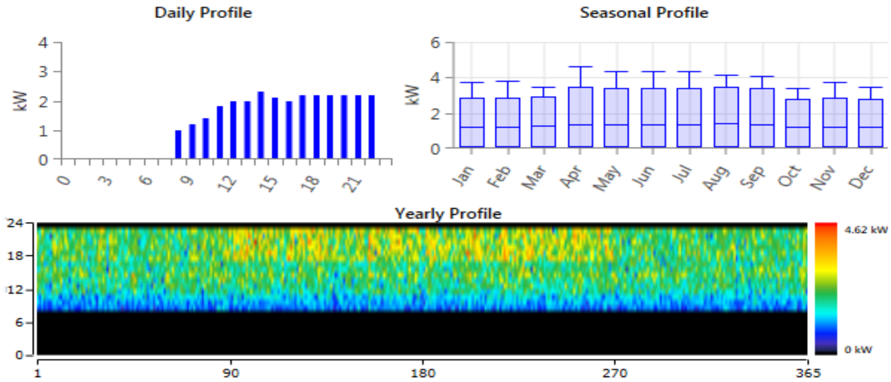


Figure 4.31: Smaller 15 hrs load pattern (load profile 1)

Hours	Bulb	Radio	Mobile	Fan	TV	Pump
		Consumption	**(kW)**			
7am-8am	0.5	3.5	0.5	-	-	-
8am-9am	-	4.0 + 0.20	1.70	-	-	-
9am-10am	-	4.0 + 0.20	1.7 0 + 0.22	-	-	1.50
10am-11am	-	4.0 + 0.40	0.22	-	-	1.50
11am-12pm	-	4.0 + 0.40	0.22	-	-	1.50
12pm-1pm	-	0.20	0.12	-	-	1.50
1pm-2pm	-	0.20	0.12	-	-	1.50
2pm-3pm	-	0.20	0.10	-	-	0.75
3pm-4pm	-	0.20	0.10	-	0.12	0.75
4pm-5pm	-	2.4 + 0.36	-	-	4.8 + 0.24	0.75
5pm-6pm	4.0 + 0.32	2.4 + 0.36	-	-	4.8 + 0.24	0.75
6pm-7pm	4.0 + 0.32	2.4 + 0.36	-	-	4.8 + 0.24	-
7pm-8pm	4.0 + 0.32	2.4 + 0.36	-	-	4.8 + 0.24	-
8pm-9pm	4.0 + 0.32	2.4 + 0.36	-	-	4.8 + 0.24	-
9pm-10pm	4.0 + 0.32	2.4 + 0.36	-	-	4.8 + 0.24	-
10pm-11pm	0.3	-	-	-	1.8	-

Domestic Load Commercial Load Agricultural Load (kW)

Table 4.11: Hourly load profile for the study area (October – March)

	Bulb	Radio	Mobile	Fan	TV	Pump
			Consumption	**(kW)**		
7am-8am	0.5	3.5	0.5	-	-	-
8am-9am	-	4.0 + 0.20	1.70 + 0.10	-	-	-
9am-10am	-	4.0 + 0.20	1.70 + 0.10	-	-	-
10am-11am	-	4.0 + 0.40	0.12	-	-	-
11am-12pm	-	4.0 + 0.40	0.12	0.24	-	-
12pm-1pm	-	0.20	0.12	3.20 + 0.24	-	-
1pm-2pm	-	0.20	0.12	3.20 + 0.24	-	-
2pm-3pm	-	0.20	0.12	5.60	-	-
3pm-4pm	-	0.20	-	5.60	-	-
4pm-5pm	-	2.4 + 0.36	-	2.40	4.8 + 0.12	-
5pm-6pm	4.0 +	2.4 + 0.36	-	2.40 + 0.24	4.8 + 0.24	-
6pm-7pm	4.0 + 0.32	2.4 + 0.36	-	3.20 + 0.24	4.8 + 0.24	-
7pm-8pm	4.0 + 0.32	2.4 + 0.36	-	3.20 + 0.24	4.8 + 0.24	-
8pm-9pm	4.0 + 0.32	2.4 + 0.36	0.80	5.60	4.8 + 0.24	-
9pm-10pm	4.0 + 0.32	2.4 + 0.36	0.80	5.60	4.8 + 0.24	-
10pm-11pm	0.3	-	-	-	1.8	-
Domestic Load		Commercial Load		Agricultural Load	(kW)	

Table 4.12: Hourly load profile for the study area (April- September)

For economic analysis the fixed capital cost, cost of equipment, maintenance, fuel cost and applicable subsidies were considered as same as hybrid 'mini-grid group-1'. Two different capital investment approaches have been applied;

1. 50% soft loan with 5% interest rate and 50% investor equity and
2. 40% capital subsidy to be provided by IDCOL, 30% soft loan with 5% interest and 30% investor's equity.

Fixed capital costs of USD 25,000 and USD 15,000 have been estimated for the larger (30kWp+) and smaller projects (4kWp+) respectively to cover the cost of power station building, equipment installations, distribution network and customer metering etc.

4.4.3.1 Results for Hybrid Mini-grid Group 3

HOMER analysed around 9,216 simulations for each of the ten different load profiles and for different hybrid system configurations having various sensitivity variables and economic constrains (i.e., capacity shortage, battery life, fuel usages, interest rate, capital subsidy, excess energy) and presents around 65 feasible models. The optimal Hybrid Mini-Grid (HMG) system configurations for designed load profile 1, 2, 3, 4 and 5 suggested by HOMER are presented in detail in table 4.13. For load profile 1, where only domestic load (110.06kWh/d) is applied, the proposed HMG 1 and 4 present the highest unit cost of electricity between USD 0.579 – USD 0.476 for no capital subsidy and 40% capital subsidy respectively. While the commercial load of 12.593kWh/d added to the regular domestic load representing 'load profile 2' for the current study the HMG 2 and 5 present the cost of electricity as USD 0.542 – USD 0.508 and USD 0.466 – USD 0.428 for no subsidy and 40% subsidized capital investment. However applying the managed load profile with extended commercial and small industrial load of 45.358kWh/d the lowest unit COE of USD 0.368 – USD 0.366 and USD 0.316 – USD 0.29 achieved through HMG 3 and 6 using no subsidy and 40% subsidy respectively. By using managed load profile HMG 6 and 3 produce only 17% and 19% of excess electricity throughout the year in comparison to 37% and 35% in HMG 1 and 7 respectively.

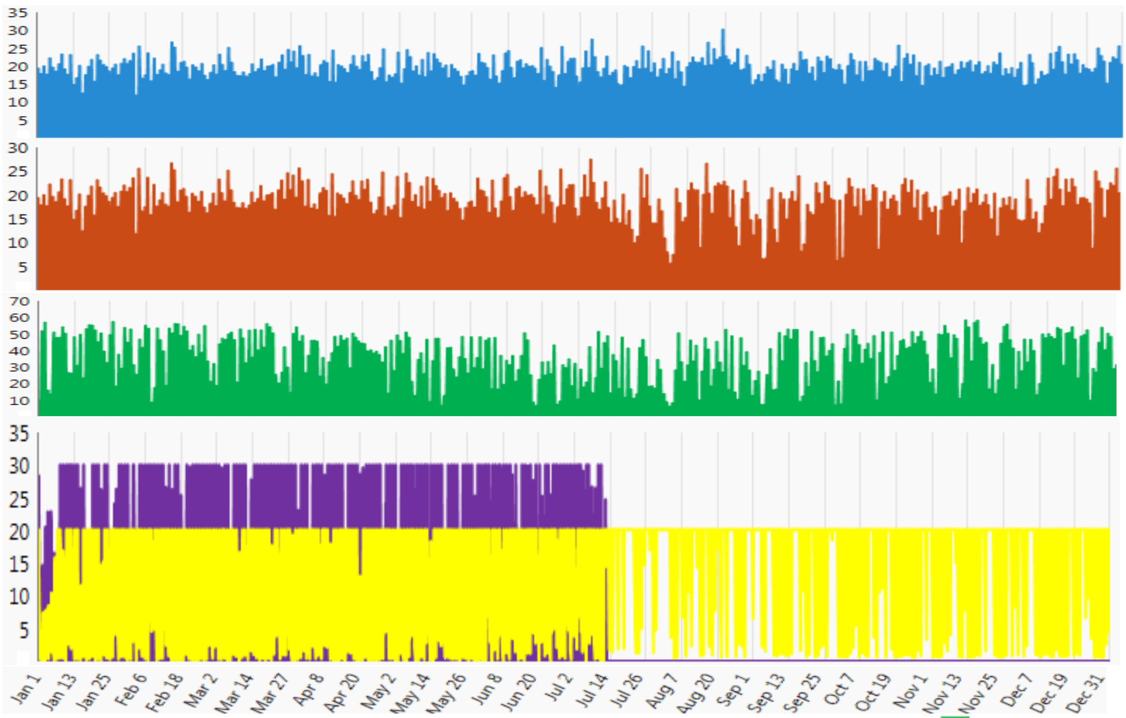
The HMG 7, 8, 9 and 10 with relatively much smaller load (load profiles 4 and 5) present very high COE in comparison to the bigger load profiles studied. Different system configurations (HMG 7 and 8) operating only 6 hours in the evening serving 14.7kWh/d represent COE as high as USD 1.39 – USD 1.34 for no capital subsidy. However, the same HMGs serving the same load profile with 40% capital subsidy supply electricity for USD 1.14 – USD 1.10. HMG 8 and 10 with different system configurations applying relatively higher combined load of 30.5kWh/d over 15 hours a day deliver electricity at a lower price of USD 0.582 –USD 0.626/kWh.

The capital subsidy used in this study (40%), showed significant reduction in COE between USD 0.13 – USD 0.25/kWh in cases of HMGs with very small loads (HMG7–10, Table 4.13). On the other hand, the same amount of subsidy applied on systems with relatively bigger loads (HMG 1-6; Table 4.13) reduces the COE ranging from USD 0.05 – USD 0.08/kWh.

Hybrid Mini grid (HMG) Architecture and applied load profile	Scaled Load profile			Load Share kWh/d		Operating Hours per day	Initial Capital USD		Cost/ year	NPC (No Subsidy) x1000	NPC (Subsidized) x1000	COE (No Subsidy)/kWh	COE (Subsidized)/kWh	Renewable Fraction (%)	Excess Energy (%)
	Annual Average kWh/d	Scaled Average kW	Scaled Peak kW	Domestic	Commercial		No Subsidy x1000	Subsidized x 1000							
HMG 1: PV 50kW, Genset 30kW, Converter 20kW, Battery 1kWh x 80; (10% capacity shortage)															
Load profile 1	110.06	4.59	30.11	110.56	-	12	87	52	13,569	262	227	0.579	0.502	55	37
HMG 2: PV 60kW, Genset 30kW, Converter 30kW, Battery 1kWh x 80; (8% capacity shortage)															
Load profile 2	122.65	5.11	30.33	110.06	12.59	16	95	57	13,685	273	234	0.542	0.466	60	31
HMG 3: PV 60kW, Genset 30kW, Converter 30kW, Battery 1kWh x90; (8% capacity shortage)															
Load profile 3	176.77	7.37	30.19	131.41	45.36	16	92	58	13,387	271	231	0.368	0.316	78	19
HMG 4: PV 40kW, Genset 30kW, Converter 20kW, Battery 1kWh x80, Wind G3x3; (8% capacity shortage)															
Load profile 1	110.06	4.59	30.11	110.06	-	12	121	72	12,059	268	228	0.545	0.476	74	31
HMG 5: PV 40kW, Genset 30kW, Converter 30kW, Battery 1kWh x90, Wind G3x3; (8% capacity shortage)															
Load profile 2	122.65	5.11	30.33	110.05	12.59	16	109	65	12,632	276	228	0.508	0.428	77	29
HMG 6: PV 40kW, Genset 30kW, Converter 30kW, Battery 1kWh x90, Wind G3x3; (6% capacity shortage)															
Load profile 3	176.77	7.37	30.19	131.41	45.36	16	109	65	12,609	287	228	0.366	0.29	84	17
HMG 7: PV 10kW, Genset 10kW, Converter 10kW, Battery 1kWh x60; (10% capacity shortage)															
Load profile 4	14.7	0.61	4.61	14.7	- -	6	42	25	4,161	96	79	1.39	1.14	91	35
HMG 8: PV 10kW, Genset 10kW, Converter 10kW, Battery 1kWh x60; (8% capacity shortage)															
Load profile 5	30.5	1.27	4.62	14.7	15.35	12	42	25	4,994	107	900	0.744	0.626	73	27
HMG 9: PV 5kW, Genset 10kW, Converter 10kW, Battery 1kWh x40, Wind G1x2; (8% capacity shortage)															
Load profile 4	14.7	0.61	4.61	14.7	-	6	44	26	3,844	93	76	1.34	1.10	93	31
HMG 10: PV 10kW,Genset 10kW, Converter 10kW, Battery 1kWhx60, Wind G1x2; (6% capacity shortage)															
Load profile 5	30.5	1.27	4.62	14.7	15.35	12	50	30	4,136	103	83	0.719	0.582	94	24

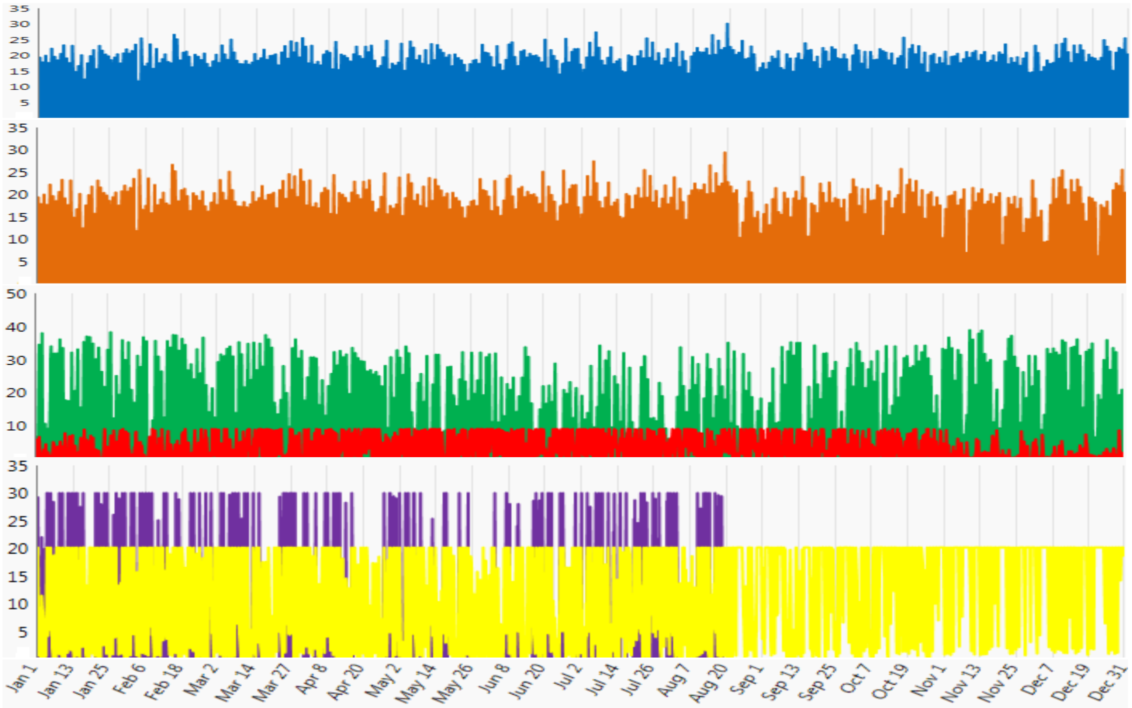
Table 4.13: Different hybrid mini-grids profile and economic features

The optimal hybrid systems identified in 'Group 3' based on the net present cost and COE are HMG 3 and HMG 6 both serving the managed load profile. A detailed time series analysis of these two hybrid systems (Fig. 4.32 & 4.33) indicates clear harmony between primary AC load demand and load served. Capacity shortage is smaller in HMG 6 (6%) than in HMG 3 (8%) as the gap between the load demand and combined power served by different components is very marginal. HMG 6 shows steady performance by all of its components, especially power produced by the wind turbine during the months of August to November, thereby reducing the dependency on generator. Moreover, the synchronized maximum charge state increases the battery life and hence reduces the cost of electricity (Fig. 4.34 & 4.35). Analyzing the nominal cash flow between two optimal hybrid systems, HMG 3 and HMG 6 (Fig. 4.36 & 7.37) it is clear that HMG 6 offers the best cash flow throughout the project life.



* All values in kW AC Primary Load AC Primary Load Served PV Power Generation Generator Power Output Battery Maximum Charge Wind Turbine Power Output

Figure 4.32: HMG 3, time series detail system performance analysis*



* All values in kW ■ AC Primary Load ■ AC Primary Load Served ■ PV Power Generation ■ Generator Power Output ■ Battery Maximum Charge ■ Wind Turbine Power Output

Figure 4.33: HMG 6, time series detail system performance analysis*

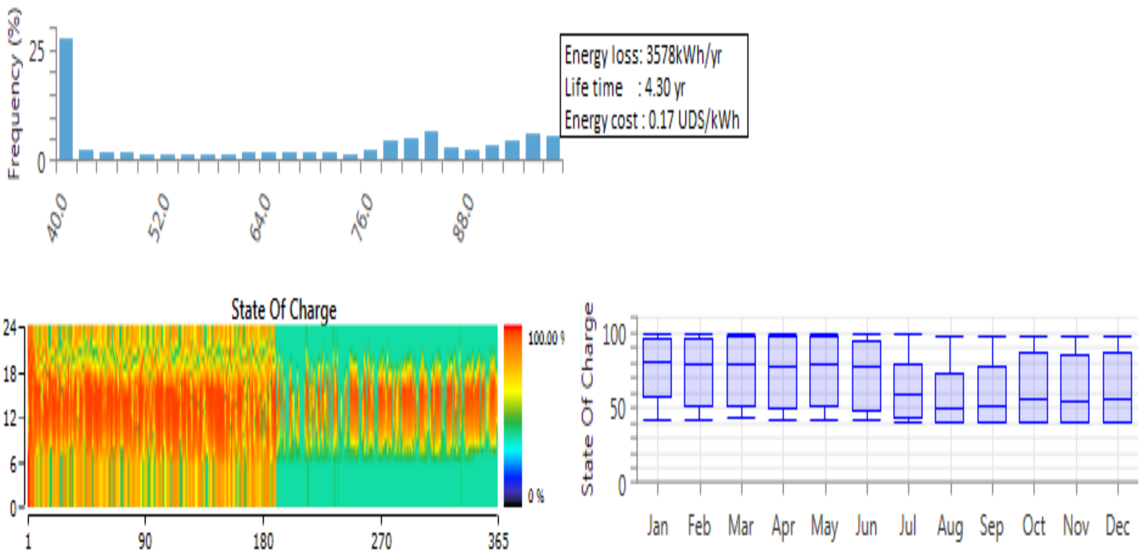


Figure 4.34: HMG 3, battery performance report

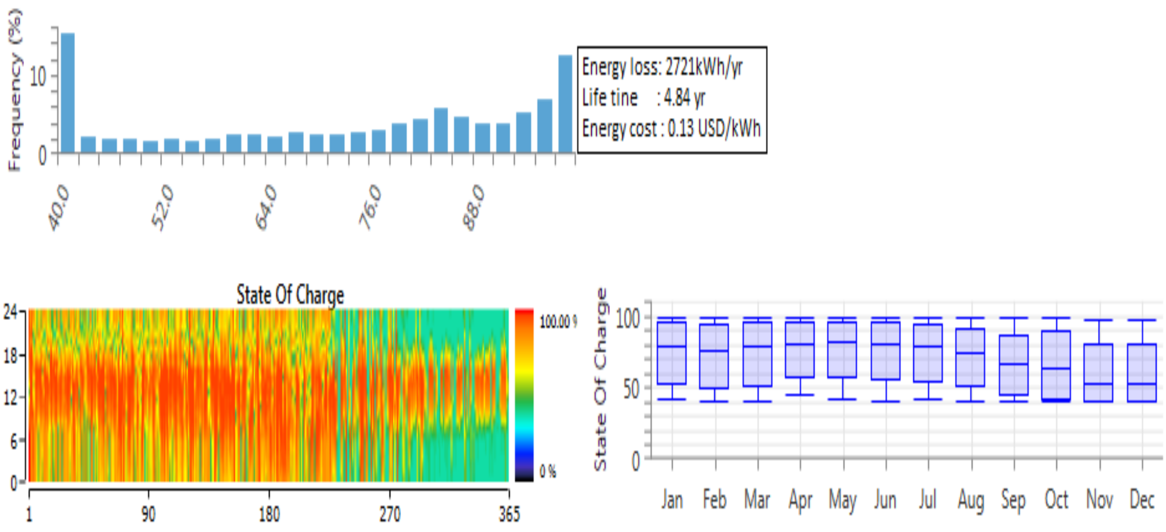


Figure 4.35: HMG 6, battery performance report

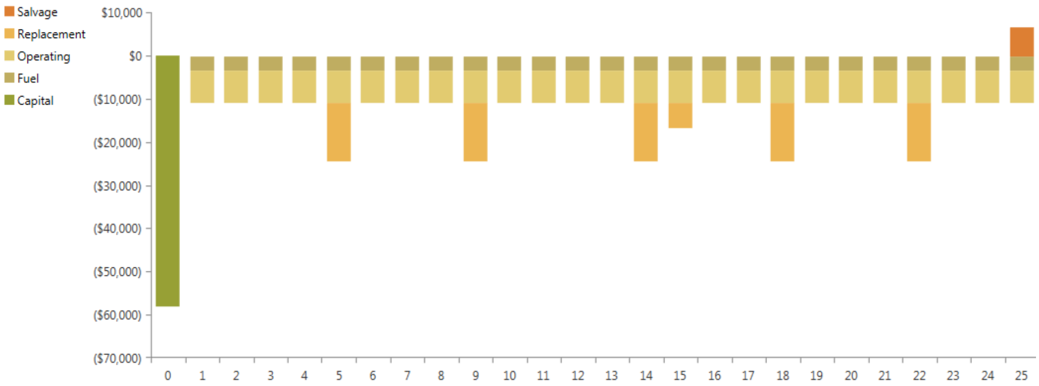


Figure 4.36: HMG 3, Nominal cash flow

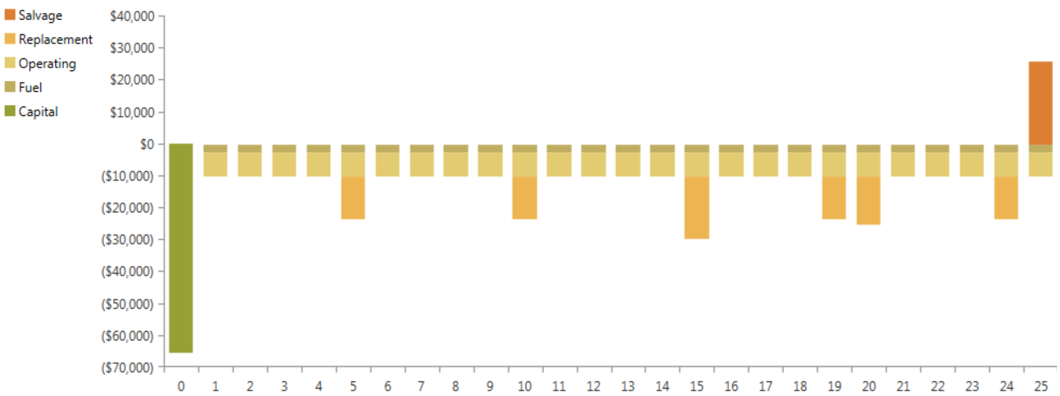


Figure 4.37: HMG 6, nominal cash flow

4.4 Discussions

Generally the renewable energy systems are cheaper to operate in comparison to conventional non-renewable systems. Decentralized renewable hybrid systems are in use in many countries supplying electricity with or without battery backup. A number of studies (Nema, 2009; Zhou, 2010; Bagul, 1996; Deshmukh, 2008; Markvart, 1996 and Beyer, 1996) tried to explore sustainable hybrid systems for small electrical loads. Mini-grids have been proven to be cost effective for electricity supply to remote off-grid areas (Manwell and McGowan, 2004; Barley et al, 1988; Fortunato et al, 1997; Hongyin, 1996; Kellog et al, 1996, Borowy and Salameh, 1994 and Abdullah et al, 2010). Most of these mini-grids are either subsidized by the governments or by donor agencies. However, acceptability of such renewable power generation approaches is well evident. Abdullah et al, (2010) showed that hybrid systems are more sustainable in terms of supplying electricity compared to stand-alone PV systems (which suffer due to prolonged cloudy and dense haze periods) and reported more customer satisfactions.

The PV-Wind hybrid systems (70kW) designed in group-1 (location 1 & 2) serving the estimated domestic load of 296kWh/d for 200 consumers in the evening considered as not feasible. The very high cost of electricity (USD 0.709–0.767/kWh) delivered by these proposed techno-economic models with total project NPC varying between USD 1.07m and USD 1.13m had an initial capital requirement of USD 462,000 to USD 579,000. The very small renewable fraction characterized by the huge size of required battery bank and heavy dependency on diesel fuel to serve only the short span of evening load (60kW peak) make these hybrid models unattractive. Contrarily, Nandi and Ghosh (2009) reported COE as USD 0.35–0.49/kWh from a similar hybrid mini-grid (serving 160kWh/d, 23kW peak) at Kutubdia Island. Their findings differ a lot with the results of 70kW hybrid systems (HMG group-1; location 1 & 2) of this study. They considered 6% interest rate on investment and 5% capacity shortage, while the present study applied 10% interest and no capacity shortage. Both studies used no capital subsidy while modelling the economic case. However, their estimated initial investment of USD 5000 and maintenance cost of USD 1000 are too little to be realistic for such a project, which might have resulted presenting the lower

COE. Nevertheless, the high COE form HMG location 1 & 2 (group-1) can be considered to be competitive with the COE from the SHS (Cela, et al., 2012).

It is believed that as a socio-economic constraint demand of electricity is relatively very low and limited to only few evening hours in rural Bangladesh. Therefore, it is very difficult to design economically viable hybrid systems with minimum fossil fuel or battery backup application to serve the concentrated evening load. Razak et al. (2007) addressed the importance of optimization of hybrid energy systems in context of reducing cost of energy by minimizing excess energy generation. Moreover, high initial cost of hybrid systems and slow return of investment justify the need to optimize the system size for reliable and cost effective energy supply (Khan and Iqbal, 2005; Razak, et al, 2007; Ekram and Ekram, 2010; Prasada and Natarajanb, 2006; Rahman et al, 2007; Kamel and Dahl, 2005; Nandi and Ghosh 2009 & 2010).

Spreading the load demand over longer hours especially when RE resources are readily available hybrid mini-grids can offer better techno-economic performance. For the 30kW Wind-PV-diesel hybrid system in this study (HMG group-1; location-4) COE reduced by USD 0.23/kWh through spreading the load over 11 hours instead of 5 hours (Fig. 4.9 & 4.10). Nandi and Ghosh (2010) reported COE as USD 0.47/kWh for a proposed Wind-PV-diesel hybrid system (160kWh/d; 23kW peak) serving 24 hour load profile at Sitakunda, a coastal region of Bangladesh, which resembles the finding of this study (Fig.4.10).

Hybrid systems using rice husk and small hydro as major RE resources (Group-1; Location 3 & 5 respectively) represented very attractive techno-economic propositions. The rice husk mini-grid system (Fig. 4.6) can produce electricity costing USD 0.094/kWh, even when serving a nominal 5-hour load without a diesel generator or battery bank (Table 4.6a). The same rice husk system can produce electricity for USD 0.172/kWh for a wider load of 11 hours. Assuming rice husk is available all the time this system should be well-anticipated compare to other hybrid systems. However, because of the availability of rice husk is confirmed to a few areas of Bangladesh mini-grid locations should carefully be considered. The only rice husk based off-grid power plan of Bangladesh in Gazipur had to cease its production because of non-availability of raw material and grid intervention. Bhattacharyya

(2014), reported two successful rice-husk power generating companies operating in rural India. These are Husk Power Limited and DESI Power. Husk power sells electricity as a 30W package for USD 2.5 per month for domestic customers and DESI Power offers 1 hour of irrigation using a 3.7kW pump for USD 1. Their retail price for electricity turns as USD 0.57/kWh and USD 0.27/kWh respectively.

The proposed Micro-hydro-PV hybrid system serving hilly areas can meet 100% electricity load from renewables (Fig. 4.10d & 4.10h) although it has been designed with diesel generator and battery bank, which increase the cost of electricity (Table 4.8). For this project in HMG group-1 capital subsidy (40%) has been considered to achieve the COE as USD 0.291/kWh. There are only a few studies regarding micro-hydro prospects of Bangladesh (Wazed and Ahmed, 2008 and Mahmud et al., 2012). None of these studies identified the expected cost of electricity from the micro hydro mini-grid. The only such 10kW (installed capacity) project in Banshkhali District, the Bamerchara micro-hydro funded by the UNDP has been able to generate less than half of it capacity (Rajan, et al., 2012). Höffken (2016), reported many small and micro-hydro projects run by non-government organizations in many areas of India. Villagers pay a lump sum of USD 2.85 per month for using electricity only in the evening from the micro-hydro power grid in the Bawan valley Borneo (Murni, et al., 2012).

The proposed 80kW PV-Wind-Diesel HMG systems designed for Chakaria (coastal region) and Naogao (northern part of the country) serving 366kWh/d load (spread over 18 hours) with 79kW peak demonstrate very efficient techno-economic performance (Fig. 4.11 – 4.19). These systems have been optimized in accordance with the diurnal and seasonal RE resources availability and required load profile. Most of the daytime load is supplied from the PV, while excess energy charging the battery bank through the load following strategy. On the other hand, wind turbines support the evening load and balancing the battery bank charging following time-lapse strategy. Naogao HMG produces electricity at USD 0.273/kWh considering 5% interest rate and 26% capital subsidy (Fig. 4.11). Considering no subsidies same system delivers COE as USD 0.335/kWh applying a 5% capital interest rate (Fig.4.14). The Chakaria HMG of same combination as the Naogao ones can produce electricity at USD 0.262/kWh without any capital subsidy and having a 5% interest rate applied on the capital. In both locations systems have been applied with very little dependency on diesel fuel and battery usages.

The different hybrid systems PV-Diesel-Battery designed for Naogao (Fig. 4.19a – 4.19d) using only solar resources as renewables showed very good prospects while serving 12 hours of wider spread load. Proposed systems in such locations can deliver electricity at USD 0.357/kWh without considering any capital subsidy and COE reduces to USD 0.308/kWh having a 40% capital subsidy (Fig. 4.19c & 4.19d). These systems are able to contribute 70% of the power shared by the solar PV and keep the COE lower. Researchers across the developing nations reported performances of different hybrid systems. Rapapate and Göl (2007) reported a small PV-Battery system in Thailand and Dalwadi, et al., (2011) reported a PV-wind-Battery hybrid system with COE as USD 1.234/kWh and USD 1.232/kWh respectively. These micro hybrid systems only serve small electrical loads in the evening and customers pay lump sum monthly. However, El-Mnassri and Leger (2010) reported a bigger PV-Diesel-Battery hybrid system delivering COE as low as USD 0.24/kWh while serving wider day and night load.

The only detailed study classifying the required electrical loads into different categories Bhattacharrya (2015), reported the unit COE as USD 0.464 for basic users (53kWh/day consumption), USD 0.368 for basic plus users (134kWh/day consumption) and USD 0.363 for reliable supply (323kWh/day consumption). While the these HMG systems applied with a 100% capital cost subsidies unit COE reduced to USD 0.39, USD 0.272 and USD 0.261 for the basic, basic plus and reliable consumptions accordingly. For the realistic business delivery model a 100% capital offset by grant or 100% capital subsidy by government cannot be considered. This research work showed that while serving relatively the same size load (366kWh/d) for a wide spread periods the Wind-PV-diesel system offers electricity for USD 0.273/kWh considering only 26% capital subsidy (Fig. 4.11) and the PV-diesel system's COE is USD 0.308 considering 40% capital subsidy (Fig. 4.19d). The Renewable Energy Policy 2008 of Bangladesh government supports this range of capital subsidy and these HMG systems can offer good business cases for sustainable rural electrification using distributed RE resources.

The most optimized HMG systems for the coastal regions of Bangladesh have been identified in Group-3 study serving 16hours of managed load profile (Fig. 4.29). The PV-Diesel (PV 60kW + Genset 30kW + Converter 30kW + 90 Batteries) and the PV-Wind-Diesel (PV 40kW + Genset 30kW + Converter 30kW + 9kW wind turbine + 90 Batteries) hybrid systems deliver electricity for USD 0.316/kWh and USD 0.29/kWh with a 40% subsidy on the capital (Table 4.13). These two hybrid system combinations represent total NPC as USD 231,000 and USD 228,000 while producing only 19% and 17% excess energy. Both the systems performance are excellent in terms of required load and delivery load matching, synchronizing battery state of charge with RE component power output and offering suitable nominal cash flow for sustainable business cases. A study (Blechinger, et al., 2014) conducted on renewable energy storage systems on small islands shows that the combination of wind power and battery storage is less favourable compared to PV-battery hybrid systems, as it is uneconomical at low wind speed. Projects serving relatively bigger electrical loads in this study represent better NPC and much cheaper COE.

Studying different HMG combinations with different resources and at different locations in this study it has been apparently clear now that a wide spread load profile is more effective and favourable for design and implementation of a mini-grid (Fig. 4.38). All the existing studies carried out by various researches in HMG feasibility studies constructed conceptual load profiles either the required load being concentrated in few evening hours or very evenly distributed over the extended day time period. However, the present research fieldwork revealed that actual electricity load demand can be managed in accordance with the power generation strategy of the proposed HMG (Table 4.12).

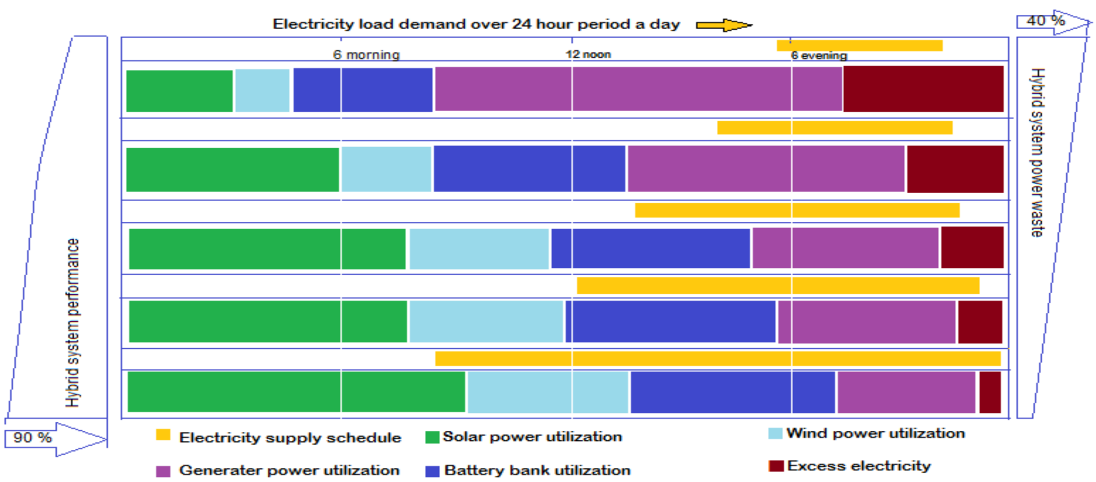


Figure 4.38: Load consumption duration (5 hours to 15 hours) and hybrid system performance for a standard mini-grid (60kW PV + 25kW Wind turbine + 65kW diesel generator + 385 string lead acid battery bank + 70kW converter) serving a load of 295-325 kWh/d with 60kW peak for different durations

Tariff is probably the most important element of successful sustainable decentralized hybrid mini-grid business model implementation. Unfortunately, no willingness to pay (WTP) study had been under taken so far for the decentralized hybrid renewable energy supply in the off-grid areas of Bangladesh. However, the present research work has carried out a complete market study at the rural level of Bangladesh. As neither SEDA nor IDCOL decide the retail price of the electricity produced by the private investors using renewable energy sources, a sustainable tariff has to be introduced by the supplier to make the project viable. Rural people in Bangladesh using stand-alone SHS actually pay USD 1.04/kWh (Blechinger, et al., 2014) and USD 0.60–0.98/kWh for using diesel grid (Khan and Haque, 2012) and USD 0.67/kWh for kerosene (Mandal, 2010). Researchers so far estimated from the most successful 100 kW PV-diesel hybrid system with battery bank in Sandwip, Bangladesh that consumers comfortably pay USD 0.41/kWh of electricity (Khan and Hauqe, 2012) and decided that average tariff ranging from USD 0.40–USD 0.45/kWh can be applied for the decentralized hybrid systems in rural Bangladesh. Interestingly, this research work has established that USD 0.432/kWh is the maximum value that the customers are willing to pay for electricity from the renewable HMGs. Therefore it is very important to carefully set the retail price for such mini-grids which can guarantee enough profit for the investors producing electricity at a cost of USD 0.29/kWh or USD 0.316/kWh.

Given that they offer electricity at a relatively low cost, these two models of HMGs become candidates for replication in the whole coastal areas of Bangladesh.

4.5 Conclusion

The bottleneck for the sustainable implications of renewable mini-grids is not the technology itself any more, but the efficient project design, its business model, financing, management, maintenance, efficient operation and integration with local socio-economic conditions as well. Actual customer market characteristic represented by a specific community may differ from the others in terms of load demand, load pattern depending on the prevailed socio-economic conditions. These characteristics of the local market need to be linked with the project design and implementations for determining the optimal configurations. Combining suitable technologies based on the availability of local resources offers sustainable solution compared to a single source generation strategy. The use of batteries as power bank and diesel generator as backup along with renewable technologies can provide rural and remote communities with effective solution for their electricity supply. This type of hybrid combination offers optimum techno-economic edge as one component supplements another whenever required. Although renewable components of the hybrid system require no fuel but their performance and productivity are related to the diurnal and seasonal availability. Therefore, combination of renewable components with battery and generator offers the independence of the hybrid system towards serving various loads required by the consumers. However, this research work only considered the lead acid batteries and standard diesel generator with fixed speed. Application of other energy storage options (i.e., Lithium Ion, Nickel Cadmium batteries) and variable speed diesel generators for achieving better mini-grid system stability and efficiency require further research.

Although the market diffusion of standalone SHS has been very impressive, a very little shift to decentralized mini grid has been initiated in Bangladesh to offer better services to the customers. A 30kW hybrid mini-grid (Wind-PV-Diesel-Battery or PV-Diesel-Battery) serving a wider 16 hours load of 131.41kWh/day (Fig. 4.29) can replace around 520 SHSs of 50Wp capacity. The total subsidized cost of 520 SHSs is USD 182,000 (IDCOL price standard) and cost of a 30kW hybrid micro-grid varies between USD 65,000 and USD 68,000 (Table 4.13). Considering this cost, an integrated marketing approach should take off the desired diffusion of distributed hybrid mini-grids.

Following the vision 2030 Master plan of the Power Division of Bangladesh, IDCOL has planned install 1,000 solar PV based mini-grids of 25kWp each in the off-grid areas of the country (PDB, 2013). Market diffusion process of mini grids may not be the same as the SHS. The major hurdle that the deployment of renewable hybrid systems faces in Bangladesh is the high initial investment cost (Urmee and Harris, 2011). The cost of diesel or petrol fuelled generators are far less than the cost of solar

PV modules of same power rating (Bhuyian, 2000). The prices of PV panels and accessories have reduced in the last ten-year period and the price of fossil fuel has gone up by many folds at the same time. Therefore, the study of Bhuyian (2000) needs to be reconsidered carefully including the running cost of the system in longer terms. The business model analysis for hybrid mini-grids in chapter-5 addressed all these issues.

*C*hapter 5

Business Model

Chapter Highlights

This chapter explores decentralized hybrid mini-grid business cases around the developing world to identify different project implementation and operation models, while focusing on private investment opportunities for the bottom of the pyramid (BOP) market. Private investment opportunities and barriers along with the related policy environment in Bangladesh have been detailed here to suggest a suitable business delivery model that can achieve economies of scale through replication and scaling up.

*C*hapter 5

5 Business Model

Renewable Hybrid Mini-grid Business Delivery Model for Bangladesh

5.1 Background

The energy poor at the bottom of the economic pyramid (BOP) cannot get the benefits of globalization without having access to the products and services that represent global quality standards. According to the traditional investment theory, as the poor have no access to enough fund to spend they are not considered as a vital sector of the conventional market. A study by Prahalad (2005) challenged this domain of assumption and argued that collectively the poor segment of a society represents a potential demand for a product or service and can exhibit considerable buying capacity. Providing product or service at a very highly discounted/ subsidized price or at no cost at all has been the most common traditional strategic approach for building consumption capacity for the consumers at the BOP. The penetration approach for such markets by offering products or services in affordable small units has been proven successful in many developing economies. Moreover, introducing innovative purchase schemes can also add capacity to the BOP consumers' buying capability. Prahalad (2012) therefore, introduced the *Four A's* (*Acceptability, Affordability, Accessibility,* *Awareness*) approach which better integrates the market at the BOP compared to the traditional McCarthy's *Four P's* (*Product, Price, Place, Promotion*). In this approach public and private sector investors should create *awareness* of the product or service in this market, create *availability*, generate *access* and finally make it *affordable*. The success of this approach in marketing renewable energy solutions has been evident in many research works (the diffusion of SHSs) in Bangladesh (Urmee and Harris, 2011; Mondal, 2010; Mithila and Sharif, 2012).

Private investment is a necessity to get enhanced diffusion of renewable technologies in decentralized mode. SREP (Scaling-up Renewable Energy Program for Low Income Countries) has been promoting renewable hybrid mini-grids (RHMG) in developing countries and invested more than USD 90 million in different project delivery models (ODI, 2014). Moreover, effective mobilization of financial resources for the deployment of RE projects serving remote areas has been a major concern both in the academic and political debate. However, in developing countries like Bangladesh low carbon electricity generation technologies are not yet commercially attractive. Therefore, several incentives and subsidies have been promoted in the recent years as major policy instruments for attracting private investment in the renewable hybrid mini-grid sector.

Interestingly, when E.ON one of the world's largest investor owned utility service provider extends its footstep into the poorest African rural market of Tanzania with its own renewable mini-grid electricity product and services there are enough reasons to believe that this is the right time for others to tap into such market around the world.

This chapter examines the renewable energy policy framework of Bangladesh along with the prevailing private investment barriers and opportunities. It finally proposes sustainable business models for the proposed hybrid mini-grids (suggested in the previous chapter-4) for the expected diffusion of this technology to achieve the goal of 'electricity for all in Bangladesh'.

5.2 Research questions addressed

In the previous chapters (chapter 1 to 4), the rationale for decentralized hybrid mini-grids as universal rural electrification tool for Bangladesh has been clearly established (chapter 1), while area specific availability of potential renewable resources have been identified for this purpose (chapter 2). The detailed market study that has been carried out for this research work offered a clear understanding of the nature of the BOP market and consumer demand (chapter 3). This detailed rural market study indicated area specific optimum hybrid mini-grids suitable for rural and remote areas (chapter 4). At this point of this research work, the designed optimal hybrid mini-grid systems need to fit into the existing policy framework to design a sustainable business delivery model.

Two research questions are addressed and suitable solutions have been identified in this Chapter. These questions are:

1. What will be the suitable business delivery model involving the private sector to make the mini-grid commercially feasible?

2. Could the suitable techno-economic model (one or more) of mini grid(s) be standardized for replication to obtain economies of scale?

5.3 Literature review

Bergek, et al., (2013) studied the renewable energy (RE) investment pattern and investors characteristics in Sweden. They argue that the common pattern of RES-E (Renewable Energy Sources- Electricity sector of European Union) investors switches among the potential renewable energy resources and technologies. This study indicates that investments in wind power generation are dominated by the IPPs (independent power producers) but such investments are very rare in solar power (PV) production. De Jager et al., (2011) show that major RES-E policy support tools designed in the recent years by the policy makers in Europe lead a bottom-up convergence. The study outlines that the policy attributes related to policy tools applied (extensive application of feed in tariff) and their possible applications (size of installations) in many EU countries are often similar. Feed-in-tariff has been established as the most successful policy instrument across many developed countries to attract private investment as it guarantees the reliable and secure return over the estimated payback period.

Mathewes et al., (2010), highlighted that the characteristics of public versus private financing and the related issues are yet to be explored for mobilizing the private investment in industrial scale that can address the challenges of global warming and climate change. However, Mowery, et al., (2010) indicated the importance of environment friendly public policy driven support initiatives for major diffusion of renewable energy technologies and argued that government can be a potential user of such technologies. However, achieving a low carbon society through a low carbon economy heavily depends on the participation of institutional private investors (Müller et al., 2011; Popp et al., 2011).

The Annual Energy Outlook (EIA, 2011) estimated the cost of electricity generation in 2016 by solar PV technologies to be USD 0.21/kWh and USD 0.09–0.10/kWh from the conventional power plants. However, in the case of small distributed renewable projects the cost of electricity will be much higher (Bloomberg, 2016). This phenomenon indicates the fact that to compete or supplement the conventional grid renewable technologies (PV, PV hybrid) need to reduce the initial capital cost by 50%. Drastic reduction in capital investment from a private sector perspective can only be achieved if the market sees a sharp fall in RE technology price or by obtaining substantial capital subsidies.

High upfront cost, low return and associated uncertainties are the main factors for the slow dissemination of renewable hybrid mini-grids across many developing countries (ARE, 2008). Different forms of subsidies are proven as effective tools for project viability. In China, under the Township electrification Program, the central and local governments paid full capital expenses and some ongoing operation and maintenance costs (Zhang and Kumar, 2011) for decentralized renewable mini-grids. Ministry of New and Renewable Energy in India offers up to 90% of the capital cost for certain renewable mini-grids under the Remote Village Electrification Program (Government of India, 2012). In Cambodia government funds support subsidies of USD 400/kW for mini hydro and USD 300/kW for biomass based mini-grids; moreover a fixed USD 45 subsidy is provided for every household connection (Kingdom of Cambodia, 2005). In Nepal around 50% of the investment in micro hydro mini-grids is subsidized by the government (UNDP, 2012). However, most of these projects are run either by the communities or co-operatives, where they are only responsible for operations and maintenance.

Solar home system's (SHS) marketing and business model in Bangladesh has been termed as a great success (IEA, 2012), although this standalone off-grid electrification approach has many limitations. Study (Chaurey and Kandpal, 2010) indicates the major competitive feature of hybrid mini-grids over the SHSs and states that mini-grids serving areas with a large number of customers in geographically flat terrain can be a better financial option both for the investor and consumer. They also reported that to be financially feasible a PV micro-grid with 1km of service network area (SNA) needs at least 180 domestic connections with each household using electrical appliance(s) of 18W for four hours daily. In the case of SNA to be extended to 4km because of the low population density in a proposed project area the required number of connection increases to 270. Palit and Chaurey (2011) argue that a 10kW hybrid mini-grid having a 2km SNA can be economically feasible while serving 100 connections. These prerequisite criteria are all applicable for specific socio-economic scenario, as studies only have considered the domestic loads but not the potential commercial and agricultural loads. However, for bigger hybrid systems and different load demand portfolio the mini-grid service network area can be all different.

Studies (Adaramola, 2012; Adaramola, et al., 2012; Ajao, et al., 2011 and Nema et al., 2009) considering the techno-economic features concluded that decentralized renewable hybrid systems are more reliable and can supply electricity at lower cost than any single source system. Adaramola, et al., (2014) studying some northern part of Nigeria reported that distributed hybrid systems are cheaper to operate in the long run compared to standalone diesel generators. Successful inclusion of mini-grids has been reported by Kumar and Manoharan (2014) in Tamil Nadu, India where electricity supply by the centralized grid is unreliable.

Most of the business models followed around the world to operate mini-grids fail to generate enough revenue to maintain the projects without further cash investment or subsidies (ARE, 2012). Lack of innovative business approaches hinders scaling up this electrification strategy for off-grid areas in developing countries. Carbon credits can be a potential revenue stream for hybrid renewable mini-grids. According to Blum et al., (2013) around 0.96kg of CO_2 per kWh of electricity consumption can be reduced by replacing the fossil fuel based energy generation with renewables. Renewable energy projects can claim carbon credit revenues ranging between USD 0.009 and USD

0.016/kWh (The Gold Standard Foundation, 2012). Perhaps, government or the affiliated organization that looks after the remote and rural electrification can bring all the small decentralized renewable mini-grids under one umbrella to claim the carbon credit jointly.

A socio-political environment with appropriate policy framework to encourage and support private investment in distributed RE technologies and scaling up mini-grid deployment can help regenerating local economy and increasing rural empowerment. Application of innovative approach in such electrification initiatives can add more sustainability to the mini-grid projects by reducing operation and maintenance costs. Therefore, business models with suitable innovative approach covering wide spectrum of project financing, system design and risk management strategies are essential to encourage private investment in this field. A market specific sustainable mini-grid business model needs be developed for Bangladesh.

5.4 Methodology

An existing mini-grid project is a final shape made out of several building blocks representing particular dimensions of economic, social, technical and institutional aspects. Standard methods for identifying or exploring a suitable business model for commercial implementation of mini-grid for a specific developing country are almost non-existent in scholarly literatures. Different business delivery models have been adopted and applied in many developing countries by both public and private sectors. A sustainable business model for decentralized hybrid mini-grids requires a set of complex interactions among different associated elements and actors. Therefore, a bottom up approach has been followed in this research work to explore the suitable business delivery model(s) for Bangladesh using the broad spectrum of elements and actors into a tailor-made framework. Knuckles (2016) and Yadoo (2012) applied the same type of approach. To explore the common business model framework for the bottom of the pyramid (BOP) market in general while covering both the conventional (fossil fuel) and renewable mini-grids Knuckles (2016) applied a four-dimension approach and these dimensions are:

1. Customer identification
2. Customer Engagement
3. Value chain and
4. Monetization

Whereas, Yadoo (2012), followed a model of *'43 indicators based on five sustainability dimensions* (technical, social, economic, environmental and institutional)', while studying several community mini-grid business models in Nepal, Kenya and Peru.

However, this research work considers only the renewable hybrid mini-grids with focus on rural Bangladesh market and it checks the suitability of different business delivery models with all sustainability elements and actors. Thus the approach of this work is different in its nature and attributes from the work of Knuckles (2016) and Yadoo (2012). Therefore, instead of just four or five dimensions this research has applied the whole spectrum of the major business elements and market actors to fit the framework for the business model(s) that would be most suitable for Bangladesh. These actors and elements are listed below and discussed in detail:

- Area specific renewable resources
- Optimized Hybrid mini-grid systems
- Nature of the target market
- Investment barriers and opportunities
- Existing policy framework
- Project financing
- Risk and uncertainty
- Existing business models
- Smart techno-economic innovation

By analyzing all these inherent elements and actors, suitable business models have been identified applying a "two-step process" for successful commercial mini-grid implementation through active participation of private sector. In the first step the suitability of private investment in this sector has been identified based on the primary data (RE resources mapping, hybrid system design & optimization and target market characteristics which have been detailed in the earlier chapters) and secondary data analyzed (policy environment, investment barriers, investment opportunity, associated risk and existing MG models & performance) using a checklist (Table 5.2a).

Finally the proposed business model with in a total mini-grid business plan has been developed in accordance with the 'decentralized renewable energy policy framework' of Bangladesh government.

Some hybrid mini-grid projects in Bangladesh have been studied during the field visit and analyzed in-depth based on available data to identify key features related to project's success or failure. The business models of Husk Power, India and Tsumkwe hybrid mini-grid system in Namibia have been investigated as well. Grid versus decentralized renewable energy price around the world, especially in some developing countries are compared to justify the proposed cost of electricity in the suggested business model.

5.5 Investment scenario in hybrid mini-grids

Investment scenarios of RE ventures, both large and small scale are well studied around the globe. However, the investment status at present is not adequate to encourage the target diffusion of the technologies by governments in many developing nations, although all countries have expressed their concern about the impact of conventional energy production on the environment and set their own target of renewable energy production. In recent years Asia and Oceania regions have attracted more than one third of the investments in this sector (McCrone, et al., 2012).

Lee and Zhong (2014) used a top down approach to analyze investment in RE portfolios, whereas Choi, et al., (2015) applied a bottom up model to explore future of RE investment in Korea. These studies were intended to identify the factors and issues that encourage or hinder the diffusion of RE investment and subsequent growth in this sector. These studies applied the theoretical frameworks built upon the technological innovation systems (TIS) and associated functions. Such theories suggest the requirement of strategic alignment of all related factors, institutions and networks for successful implementation of proposed TIS. Notably, the transition of a specific TIS from the initial stage to the growing phase can be affected by several factors (Jacobsson and Bergek, 2004). Identifying such factors and resolving the issues create the base for developing and applying strategic policy tools. The process associated with the innovation, application and diffusion of any RE technology project in a specific socio-economic environment should be analyzed by considering the available technological knowhow, associated actors and the existing policy framework (Malerba, 2005).

5.5.1 Investment barriers

Studies (Cárdenas-Rodríguez et al., 2013; De Jager et al., 2011; Haley and Schuler, 2011; Kenney and Hargadon, 2012; Müller et al., 2011) identify the high initial cost, slow return, long payback period, unforeseeable risks, complex policy environment and poorly explored market/ consumer as the major factors hindering the institutional private investments in decentralized mini-grid based electrification. The perceived risk and expected return profiles of mini-grid projects are directly related to these factors, which reduce the scopes for institutional investments (Cárdenas-Rodríguez et al., 2013; Dinica, 2006).

Technology is not considered as a major hurdle anymore for successful mini-grid implementation whether it is powered by a single source or by a hybrid combination of energy sources. The real challenge lies primarily with the optimal design and combination of the technologies and finally the financial viability of the project poses the main challenge, as the individual load demand in the rural and remote areas remains low. Therefore, the traditional approach of serving such market may fail unless innovative business models addressing the issues are in place. Considering all these facts ODI (2014) concluded that the 'one-size-fits-all' strategy needs to be replaced by the area specific tailor made solutions considering the socio-economic conditions and policy environment.

These barriers can stem from stakeholders at the local, national or international level, i.e., the same levels as the adequate revenue sources. The barriers can translate into investment risks in the planning, construction and operational phase, which might discourage investors from investing (or increase financing costs and thereby the generation costs), which may force the projects to fail (Glemarec et al., 2012 and Waissbein et al., 2013).

Even though research on rural electrification through renewable energy is increasing, most studies address the engineering, development and techno-economic aspects. The private sector's investment decisions remain poorly researched (Bhattacharyya, 2011, Bhattacharyya, 2012 and Kaundinya et al., 2009). Several reports (Bhattacharyya, 2011; Schäfer et al., 2011; Glemarec, 2012 and Zerriffi, 2011) recommend further research with regard to scaling up diffusion through private investments.

The Bangladesh government has been promoting its remote area electrification program by encouraging the renewable energy diffusion. Unfortunately, the huge gap between the unit prices of electricity produced from RE sources and the grid is considered to be the main bottleneck. To achieve the grid price parity from a distributed RE mini-grid the required amount of capital subsidy and operating subsidy may create unbearable financial burden on the government which is very unusual to be sustainable (Bhattacharyya, 2015). Moreover, use of poor quality equipment, poor installation, lack of quality assurance, lack of trained manpower and knowledge base and overall poor and complex policy implementations are identified as the hurdles in many academic reports (Bhattacharyya, 2015; Mandal, 2012; and Mujeri and Chowdhury, 2013).

5.5.2 Investment opportunities

Compared to the extension of the central grid, decentralized hybrid mini-grids can be a less expensive option due to lower capital cost of infrastructure (depending on distance) and lower operating cost by avoiding transmission and distribution losses. Hybrid mini-grids can provide better quality electricity and service compared to standalone systems, i.e. Solar Home Systems, batteries, solar lamp etc. ARE (2013) carried out the most inclusive study of hybrid systems and their existing business models in many countries and concluded that decentralized hybrid mini-grids can be a financially feasible solution while offering area specific services.

Rural electrification through decentralized mini-grids should have a tariff designed that can recover at least the operation and maintenance cost of the hybrid system, which termed as the breakeven tariff if the project is run by public utility. However, in case private investor owns the mini-grid the retail tariff must generate a substantial amount of profit for the project to be viable. While setting the unit price of electricity to be supplied by hybrid mini-grid, the customers' willingness to pay (WTP) needs to be carefully considered. A single or combinations of subsidies (i.e., capital investment subsidy, operational subsidy, tariff subsidy) are proven tools to balance the generation cost and tariff (van Ruijven, et al., 2012).

Subsidy of the initial investment may deliver the required solution if it combines with a sustainable tariff. In some cases tariff subsidies may also be an effective powerful tool to encourage private investment. However, policy supporting the subsidies in any form should be designed in such a way that these are only used to encourage private investment at present by lowering overall cost of the project to offer an affordable tariff and hence achieving mass penetration. Through mass penetration, economies of scale can be achieved and subsidies can gradually be reduced and finally eliminated. The famous theory of the World Trade Organization in this regard is, *"subsidized investments and business development should lead to lower costs through enhanced learning curves and economies of scale to a point where subsidies become unnecessary. Hence, subsidies should always integrate a phasing-out process, and be self-eliminating" (WTO, 2006).* The SHS dissemination process in Bangladesh does justify this theory. It is evident that the amount of subsidy per unit of SHS has been reduced over the course of time while the penetration of the technology has been increasing (Fig. 5.1).

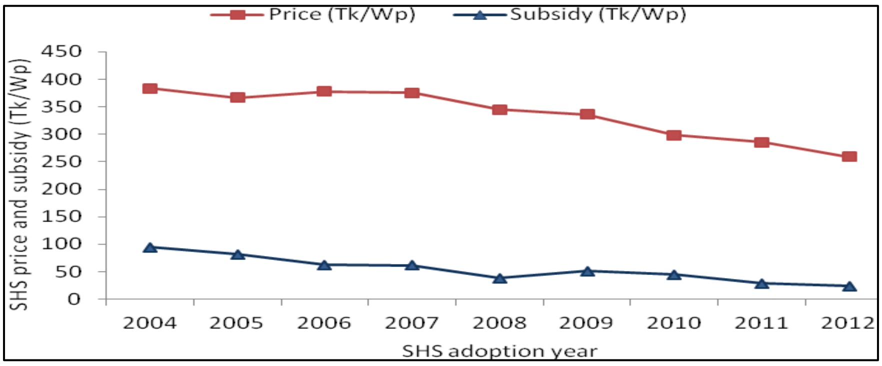


Figure 5.1: Change in SHS price and subsidy over time (Source: Samad, et al., 2013)

The key lesson from the SHS dissemination in Bangladesh experience is that, for scaling up the adoption of renewable energy technology, it depends critically on private sector participation, while public sector support is crucial at the initial stage, by means of financing, subsidy, technical assistance, institution and human capacity building, until a critical mass is reached for scaling up.

'Carbon finance' can be used as a secondary funding tool for renewable energy projects. Despite the uncertainties related to the 'Kyoto Protocol' such funding may lead to a low carbon economy. It has been estimated that by 2020 a convergence of USD 120 to USD 150 billion annually of investment in low carbon technologies could be created by the carbon offset market (UN AGF, 2010).

The application of carbon finance in small-scale low emission energy technologies may play a significant role towards universal access to energy. Reports (Brinkmann and Klingshirn, 2005; Limmeechokchaia and Chawana, 2006 and Gibbons et al., 2009) show that around 50 to 70% of fossil fuel could be saved by modified (fuel efficient) cooking stoves. IDCOL estimates that USD 61.80 worth of kerosene can be saved each year by a standard size of SHS, which results in reducing 375 kilograms of carbon dioxide emission. According to Husk Power India each plant helps avoid 125 to 150 tons of CO_2 per year, which can be monetized through Certified Emission Reductions (CERs). Notably, while considering small scale renewable energy projects the rigid requirements in complying with the Clean Development Mechanism (CDM) regulations on project baseline and the complex process of registration, monitoring and validation the increased transaction costs can prohibit their access to 'carbon finance'. However, it is possible to recover part of the cost of the investment by using the carbon credit if the small projects are combined. For example, the highest provider of SHSs in Bangladesh, the Grameen Shakti has managed to have a deal with the World Bank for carbon financing by signing an agreement under the CDM.

5. 6 Renewable Energy Policy Framework of Bangladesh

It is important to understand the key structure of the Bangladesh electricity board, which is directly related to the renewable energy policy implementation of the country. The whole energy sector including the electricity is under the Ministry of Power, Energy and Mineral Resources (MPEMR). At present the entities responsible for different functions of the electricity sector in Bangladesh are as below:

Generation: Bangladesh Power Development Board (BPDB), Rural Electrification Board (REB) and Independent Power Producers (IPPs).

Transmission: Bangladesh Power Development Board and Power Grid Company of Bangladesh Ltd. (PGCB).

Distribution: Bangladesh Power Development Board, Dhaka Electric Supply Authority (DESA), Dhaka Electric Supply Company Ltd. (DESCo) and Rural Electrification Board (REB) through different Palli Bidyut Samities (PBSs).

Development partners: Sustainable Energy Development Agency (SEDA), Sustainable and Renewable Energy Development Authority (SERDA), Local Government Engineering Department (LGED), Bangladesh Energy Regulatory Commission (BERC) and Infrastructure Development Company Limited (IDCOL)

Among all these entities, SEDA and IDCOL are directly related to the renewable energy policy implementation and generation in Bangladesh. IDCOL has established itself as the 'light house' in off-grid rural electrification.

The complete Renewable Energy Policy of the country was finalized and approved in 2008. The strategic objectives of this final policy are:

- Promoting RE technologies for harnessing energy from renewable sources
- Encouraging private investment
- Producing 5% of energy from renewables by 2015 and 10% by 2020
- RE based electrification in rural areas

According to the guideline of the policy, Sustainable Energy Development Authority (SEDA) has been formed as an institutional arrangement. SEDA will have the responsibility of upholding the objectives of the 'Renewable Energy Policy of Bangladesh 2008' by taking different initiatives:

1. Promoting awareness of renewable energy technologies and supporting new technologies and business models.
2. Supporting establishment of small and medium renewable energy enterprises by creating market opportunities and business models for rural energy providers.
3. Develop financial mechanisms and opportunities by using grants, subsidies and/ or carbon/ CDM fund for investors.
4. Support human resource development and local production of renewable energy equipment.

The policy has clearly developed an 'Investment and Fiscal Incentive guideline', where SEDA formulates fiscal incentives and considers subsidies to the investors in the renewable energy projects. The guideline further elaborates the policy by stating that:

5. Private sector investment including joint venture will be encouraged.
6. GOB/SEDA may assist investors in locating the project(s) and acquiring land for this purpose.
7. Investors in this field will be exempted from corporate income tax for 15 years.

Some important points related to the promotion of renewable energy technology, production and supply have not been covered in the Renewable Energy Policy of Bangladesh 2008. However, Bangladesh government gazette (Reg. no. D A-1, dated July 26, 2007) declaring Remote Area Power Supply System (RAPSS) included important policy initiatives in its guideline:

8. Investors or utilities will be allocated with RAPSS area of choice (either off-grid or on-grid) to produce and distribute electricity for a period of twenty years
9. An allocated RAPSS area should preferably be contiguous and include the entire area of two or more upazilas. Several areas under 15 administrative districts already have been selected by the government (Fig. 5.10).
10. Investors may have access to RAPSS fund in the form of connection fees subsidy to get increased customer penetration (having connected load less than 300watt) for a maximum period of seven years.
11. Incase of capital cost subsidy, the amount should not be more than 60% of the installing generation plant in RAPSS area.
12. To achieve competitive tariff additional subsidized loan may be provided to the investor.

Neither the final 'Renewable Energy Policy 2008' nor the RAPSS guideline clearly demonstrate any policy highlighting the retail pricing of electricity generated by the decentralized mini-grid systems. The 'Draft Renewable Energy Policy 2002' had a clear outline regarding the pricing policy. The draft policy stated that, "*GOB will not regulate the price of electricity generated from renewable energy source which shall be negotiated between the sponsor and the consumers but ERC will protect the interest of both the sponsors and the consumers*".

5.7 Hybrid Mini-grid business models

As stated earlier, Bangladesh failed to achieve any significant success in commercial decentralized hybrid mini-grid implementation, although it has a favourable renewable energy policy supporting such ventures. Three major mini-grid projects have been discussed here along with the latest feedback from the site visits, which will provide clear pictures of the status of present diffusion of this technology in Bangladesh and the real gaps between the policy in the book and actual implications. Finally, the business model of 'Husk Power India' and 'Tsumkwe hybrid mini-grid', Namibia have been analysed in brief to get a comparative idea for the bottom up analytical approach in this research.

5.7.1 Successful hybrid mini-grid in Bangladesh

5.7.1.1 Project background: Purobi Green Energy Limited (PGEL) a private company chose non-electrified Sandwip Island off the coast of Bay of Bengal to supply electricity from a hybrid mini-grid. In September 2010, PGEL started producing and distributing electricity from a 100kW PV-Diesel (100kW PV and 40kW diesel generator) hybrid power plant through a local mini-grid (Picture 5.1). The project primarily started to serve the Enam Nahar Market and some domestic customers. However, it had a target of 400 residential connections.

PV array (100kW) — Mini-grid distribution network

Battery bank — System control room

Picture 5.1: PGEL 100kW solar PV-diesel hybrid power plant in Sandwip Island, Chittagong (Photo credit: Author; December 2015)

The total initial investment was Tk56.78 million (USD 0.73million) covering the cost of site development, hybrid system installation, distribution grid and connections. The financing structure was dominated by the investment subsidy (50%) from IDCOL and PGEL had equity of 20% alongside the 30% loan on low interest (6%). The project aimed to supply electricity from 9am to 11pm throughout the year.

5.7.1.2 Operating success: The project consists of a 4km distribution grid for supplying electricity to the local schools, offices, markets and households. The hybrid system uses 60% of the PV generation capacity to supply directly to the customers during the day and 40% of the energy is stored in the battery bank to be supplied during the night time.

Local residents that previously used to get electricity from a private diesel grid took nearly a year before they decided collectively to switch to the PGEL's mini-grid. Its standard of service gained the confidence of the local people and the number of domestic connections reached to 260 by the early 2014.

5.7.1.3 Tariff structure: The supply from the diesel grid used to charge at a daily basis of around Tk46 to Tk76/kWh (USD 0.60-0.98). The cost of electricity from this diesel grid used to vary with customer types, i.e., commercial users used to pay more than the domestic consumers. PGEL charges TK32/kWh (USD 0.41) (Khan and Haque, 2012) and this tariff is well accepted by the consumers here. The locals accepted the higher tariff from the diesel generator, as they had no other alternative.

5.7.1.4 Bird's eye view: The 100kW hybrid system's monthly average production as on 2013 was 12,110kWh, which secures a revenue income of around USD 5000 per month. Accounting for the 50% subsidy on the total cost (USD 0.73m), the actual investment of PEGL was USD0.365m. The project should recover this investment in the 7th year (including interest and maintenance). However, in reality that may not happen, as the project's output had declined in recent years (Fig. 5.2). Although this project is currently undergoing some adverse situations (which are discussed later in this chapter), it has contributed to low-carbon commercial distributed power generation (Fig. 5.2).

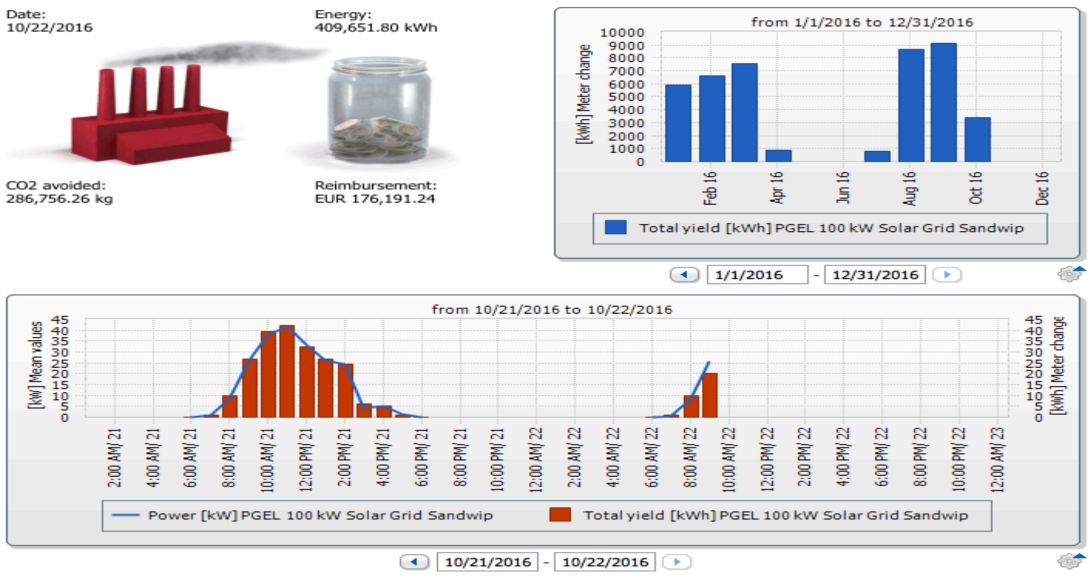


Figure 5.2: Up-to-date performance of the 100kW PGEL mini-grid, Sandwip (Source: sunnyportal.com)

PGEL installed the project by itself. It owns it, runs it and does all the revenue collection. During the project visit in December 2015, it was reported by the project manager that a local Member of Parliament convinced the government to install two 500kW capacity diesel generators to be run by Polli Bidyut Samiti (PBS) on behalf of BPDB. The proposed diesel grid will supply electricity at a very highly subsidized price of USD 0.12/kWh. This politically motivated public utility intervention contradicts the government's renewable energy policy and puts PGEL mini-grid's future in risk.

5.7.2 Failure story: Rice Husk-Diesel Hybrid system

5.7.2.1 Project background: Dreams Power Private Ltd. (DPPL) started commercial operation of a Rice Husk based power plant backed up with a diesel generator in October 2007 (Picture 5.2). The project was located in Kapasia under the Gazipur district. The cost of the 250kW project was around Tk. 2.5crore (USD 0.32million). Project finance was arranged of a 60% grant from World Bank, 20% as soft loan provided by IDCOL and DPPL invested 20% as equity. A mini grid had been constructed to produce and sell the power to the adjacent areas. The plant required approximately 1.6-1.8 kg of rice husk to generate one kilowatt of electricity. It had a target to serve at least 100 commercial customers and 200 households.

Operational condition (2008)* Project abandoned (2015)

Picture 5.2: *Now and then* of the DPPL 250kW Rice husk mini-grid power plant in Gazipur (Source: *practicalaction.com and author)

5.7.2.2 Operating failure: The project has been abandoned since 2013. After commissioning it only had an installed capacity of 56kW and managed to supply only around 200kWh/day to 50 houses (Mondal, 2013). The project failed to obtain target connections (customer) and could not source enough raw material (rice husk) for power generation.

5.7.2.3 Tariff structure: DPPL set the unit price of electricity at Tk.5.0 (USD 0.06), although no tariff subsidy was agreed. This retail pricing did not even cover the cost of generation.

5.7.2.4 Bird's eye view: Apparently the set retail price of electricity was too low for the project to be sustained. The loss of the plant could be minimized by relocating the plant to rice mill cluster areas and by utilizing the ash generated from rice husk (Islam and Mondal, 2013). Whatever the loss minimizing measures that could have been taken, these might not be enough to make the project sustainable unless the price of electricity was increased. Bhattacharyya (2014) reported COE from a proposed rice husk plant in Bangladesh ranging between USD 0.15 and USD 0.19/kWh. Similarly, this research study obtained the COE form almost same rice husk plant to be USD 0.173/kWh (Chapter-4; Fig. 4.6a). Moreover, the duel fuel generator, which used diesel to substitute the lower heating value of the producer gas also substantially, increased the cost of power production.

Failure to get target connections (customers) and inefficient technology setup along with the COE deficit created huge burden of loan repayment and accumulated overhead coast. Moreover, the final nail in the projects coffin was hammered by Polli Budyut Samiti's (PBS) grid intervention.

5.7.3 Projects of hope: Kutubdia Wind-Battery hybrid project

5.7.3.1 Projects background: The 1000kW Wind-Battery hybrid project in Kutubdia considered as fairly successful during the very first few years of operation. Later on projects had been shut down for many years for different reasons. Subsequently, steps have been taken in the recent years to revive these projects.

Project in 2016 Project in 2008

Picture 5.3: Kutubdia wind farm (Source: The Daily Star, 2016)

In 2008 the hybrid system energy started supplying electricity to the remote off-grid islanders. Pan Asia Power Services Ltd., a private company installed the project under BPDB's supervision at a total cost of USD 1.9 million near the Puratan Santi Bazar on the coastlines (Picture 5.3). The key features of the project made it unique as a decentralized RE mini-grid. These are:

- Grid quality electricity supply with 10km of 11KV distribution line
- 50 wind turbines of 20kW each and 1000 batteries of 12V, 200AH
- 11KV grid substation

Project started to supply electricity to 12,000 subscribers including those that had a connection from the PDB's diesel mini-grid as part of the strategy to replace the 500kW diesel generator with the renewables. Within a few months, the plant failed to supply the target amount of electricity mainly because of several natural disasters (super cyclones CIDR in 2007 pre-project stage and NARGIS in 2008 post-project stage) that hit the project and part of it sank in to the sea due to continuous coastline erosion. Measures have been taken by BPDB to reinitiate this project by allocating regeneration funds. BPDB learnt its lessons and undertaken another wind project of

600kW about two kilometre inside the coastline at a cost of USD 1.03 million. Pan Asia Power will implement the project and produce the electricity but distribution will be maintained the BPBD.

5.7.3.2 Operating Success and failure: BPDB used the benefit of its existing diesel mini-grid (500kW) distribution network to minimize the retail COE and decentralized the operation and distribution activities by handing it to Pan Asia Power Ltd, the private company who actually carried out the project implementations. Pan Asia neither had access to any urgent disaster management fund through BPDB nor could it generate enough funds through revenue collection, as the tariff was too marginal to do so. At present only 111 residential customers are getting very limited hours of electricity supply. Although BPDB took a long time (8 years) to allocate funds to repair the project along with some tariff restructuring, this project has managed to maintain hope among the local people.

5.7.3.3 Tariff Structure: PBDB estimated that these projects cost Tk8.00 (USD 0.103) to produce per unit (kWh) of electricity. Therefore the retail tariff was set as:

Tk. 5.5 (USD 0.071)/kWh for residential customers
Tk. 9.5 (USD 0.122)/kWh for commercial customers

BPDB assumes that its tariff structure is smart enough to keep the project sustainable for future operation. However, as the retail price of electricity for the residential customers has been set below the generation cost, the successful operation remains a big challenge. For example, Bergey Wind Power project in China failed to sustain although the whole project was subsidized under the National Township Electrification Program. The main reason of failure was the unrealistic tariff application. Cost of generation from wind technology was USD 0.24/kWh whereas electricity had been supplied at USD 0.09/kWh. The project failed to regenerate enough revenue to keep the project running (World Bank, 2008).

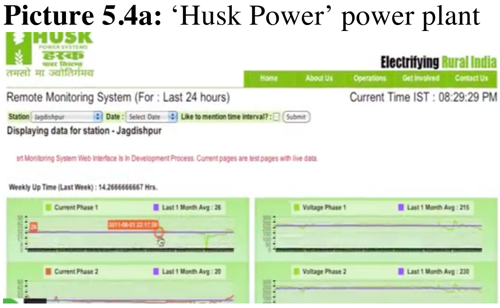
5.7.3.4 Bird's eye view: This wind-battery hybrid project did not run even for a year in its full capacity due to various problems. One of the main issues was lack of available disaster management and post-disaster recovery funds. BPDB funded the project through grants and subsidized the retail COE to help the private operator comfortably run it. However, very close proximity of the project to the coastline and unavailability of required maintenance funding through revenue collection have been two main reasons for the project failure. However, new initiatives of BPDB including adoptive disaster management for this project and the new project remain as a hope.

5.7.4 Husk Power Systems India

5.7.4.1 Project highlight: Husk Power Systems (HPS), India currently serving over 200,000 people in 300 villages of Bihar through its 84 power plants (25kW to 100kW) fed by available biomass resources. A typical plant serves two to four villages depending on size and population (Figure 5.4a & 5.4b). HPS implemented innovative income streams to enhance value creation of its plants. Bio-char and silica precipitation are recycled as by products to add income to the project and offering income generation for the local women at the same time (Figure 5.4d). It uses cloud-based remote monitoring systems for a number of plants in a wide geographical area to reduce operational cost and offer efficient service (Picture 5.4c). Through rural electrification and income generations HPS contributed to poor community development to a greater extent (Picture 5.4e).

Picture 5.4a: ‘Husk Power’ power plant

Picture 5.4b: ‘Husk Power’ village grid



Picture 5.4c: Remote monitoring

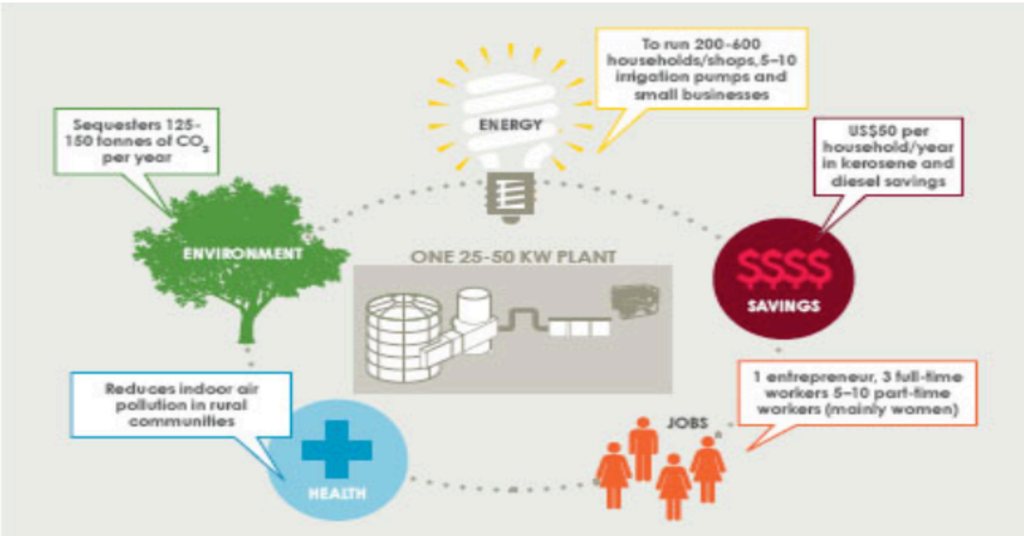
Picture 5.4d: Incense stick production

5.7.4.2 Operating success: HPS followed adaptive business models. According to Bhattacharyya (2014) it initially started with the BOOM (Build, Own, Operate and Maintain) business model by securing funds and subsidies. Later HPS moved on to

BOM (Build, Own and Maintain) model and finally emphasized on the BM (Build and Maintain) model. The smart step of HPS to establish itself as the technology supplier has created a huge opportunity for more private investor participation and more socio-economic development.

5.7.4.3 Tariff structure: HPS delivers electricity on a pay for use basis. Consumers pay USD 2-3 per month for up to two fluorescent lamps and one mobile phone charging point for four to six hours a day. It also offers customised tariff to fulfil varying needs of every different customer. On average, customers save 30% in cost in comparison to kerosene usages. However, it is evident that consumers pay around USD 0.72/kWh (*assuming that 2 bulbs @5W each and 1 mobile charger @10W used for 6 hours a day and USD 2.00 paid/month*) for the electricity supplied by HPS.

5.7.4.4 Bird's eye view: So far HPS has been successful in providing electricity to the poor rural villagers in Bihar. However, its target expansion of two thousand plants by 2014 has not been achieved for many reasons (i.e., lack of investment fund, management inefficiencies etc.).



Picture5.4e: Social impact created by HPS business initiatives (Source: HPS)

HPS ensures enough revenue return by selling electricity at around USD0.72/kWh, which in turn makes its projects commercially viable.

5.7.5 Tsumkwe hybrid mini-grid Namibia

5.7.5.1 Project background: NamPower, Namibia's government utility planned to install a 150kW PV-diesel-battery mini-grid in Tsumkwe (Picture 5.5). The project was implemented in 2012 and replaced the existing expensive diesel grid. The USD 4.3 million EU funded project took six years to be realized. The initial plan of having PV-battery hybrid system was later changed to PV-diesel-battery combination to save generation cost and to smoothly meet the peak load requirements. PV supplied 50% of the 24-hour load demand and the rest is covered by the diesel generator and battery bank.

5.7.5.2 Operating complexity: NamPower tried to privatize the project through the Desert Research Foundation of Namibia (DFRN), a NGO at the early stage. The plan did not seem viable. Later NamPower intended to create the TESco (Tsumkwe Energy Supply Company), a publicly owned IPP (individual power producer) to run the project.

Old diesel tanks New PV array

Picture 5.5: Tsumkwe hybrid mini-grid Namibia (Source: RECP, 2014)

Because of complex regulatory framework this initiative had been discarded and finally the project was decided to run as a public asset by different government entities:

1. OTRC, the Local Government owns the project, collects revenue and funds fuel.
2. Ministry of Public Works carries the operation and maintenance.
3. ECB, the Electricity Control Board oversees tariff and service quality and holds the generation licence.
4. NamPower provides technical support.

5.7.5.3 Tariff structure: NamPower replaced the USD 0.43/kWh supply from the diesel grid with a lower tariff of USD 0.11/kWh for residential and USD 0.18 for commercial customers from the renewable hybrid mini-grid. The operator provides the average tariff subsidy of USD 0.14 per kWh.

It is clear from the above case studies that a successful renewable mini-grid project needs to have a sustainable retail tariff in place so that it can generate enough revenue from sales to recover the operation, maintenance and necessary replacement costs and to ensure sufficient profit for making the project financially viable. Therefore, identification and implementation of the right business model considering the socio-economic and policy environment is necessary.

5.8 Grid versus decentralized RE based electricity price

Grid electricity retail prices vary around the world. It is obvious that retail electricity price is related to purchasing power of the consumers (Fig. 5.3). However, exceptions are evident in many countries, which need more detail explanations. Exceptions are mainly related to the local socio-political aspects.

In recent years, the Bangladesh government has made different power purchase agreements (PPA) with the rental power plants ranging from Tk 9.75 (US$ 0.13) to Tk 22 (US$ 0.29) per kWh, while supplying them gas or liquid fuel at a subsidized price. Bangladesh Power Development Board (BPDB) supplies electricity to consumers again at a subsidized price.

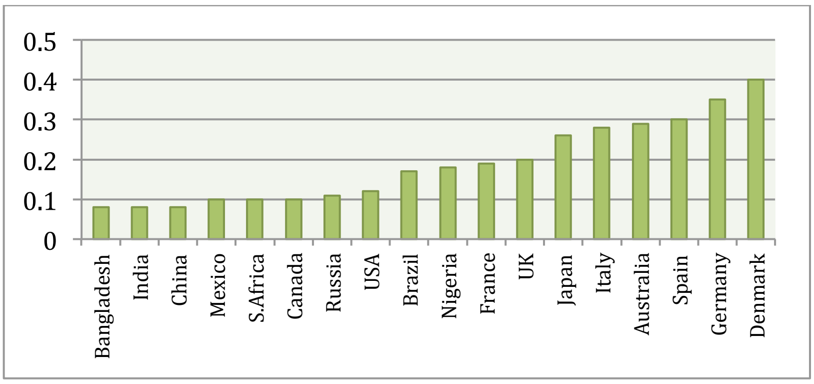


Figure 5.3: Electricity retail price worldwide (USD/kWh) (Source: IEA, 2012)

(USD0.08/kWh). However, as the selling price fell behind the rising cost of electricity supply, the government subsidy support to BPDB increased from Tk. 1,007 crore (USD129.4 million) in 2008-09 to Tk. 6,357 crore (USD 817.3 million) in 2011-12 (Mujeri and Chowdhury, 2013). The five state-owned electricity distribution companies have recently proposed to increase retail power tariffs by 8.59% to 23.50% per unit (kWh). Surprisingly, steady growth of SHS has been observed in Bangladesh although the LCOE is around UDS 1.04/kWh for a typical 40Wp system (Akhi and Islam, 2014). On the other hand, the 100kW hybrid mini-grid in Sandwip Island has been supplying electricity at USD 0.41/kWh and is currently facing huge challenge by government's political motivations.

The average grid electricity price for the end user in India is USD 0.08/kWh. However, the retail price varies among different states and areas. For example, the retail price in West Bengal is around USD 0.09/kWh, whereas the unit price is USD 0.03 in Goa. Most of the decentralized mini/micro-grids operating in remote areas in India supply electricity at a fixed fee of USD 2-4 per household per month basis for a limited use of one or two florescent light bulbs, a mobile phone charger etc. for five to six hours a day. Renewable hybrid (or standalone) systems ranging between 1kW to 20kW are supplying electricity for 4-5 hours a day mainly for lighting purpose in many remote and rural areas of India (Kumar and Banarjee, 2010).

African countries represent a wider range of tariff between USD 0.04 /kWh (subsidized tariffs) and USD 0.26/kWh (non-subsidized tariffs) for grid electricity (IMF, 2008). The prices for LCOE from SHS here vary widely between US$ 1.37/kWh and US$ 1.72/kWh. Typical mini-grid retail tariffs in Africa encompass a wide range from USD 0.113/kWh to USD1.358/kWh, depending on the technology, the operator model, the regulatory framework and financial mechanisms. In Somaliland and Puntland private sector investors supply most of the electricity in the urban and pre-urban areas from the mini-grids powered by diesel generators and consumers pay USD 1.2/kWh (GVEP, 2011).

Studies so far revealed that people in off-grid areas around the developing world generally pay many folds for their limited amount of electricity usages in comparison to their grid-connected counterparts. Simultaneously, the field study in this research work found that rural people in Bangladesh are willing to pay USD 0.40/kWh for electricity supplied from the renewable hybrid mini-grids. This finding paves the way to design sustainable business model for hybrid mini-grids in Bangladesh.

5.9 Proposed hybrid mini-grid systems and their COE

Alliance for rural electrification (ARE, 2012) estimated the levelized cost of electricity for different hybrid combinations (Table 5.1). To make a project commercially viable mini-grid operators need to sell electricity at a higher price than the actual cost of generation, which might go beyond the affordability of the rural consumer. Therefore, to set the retail price at an optimum level considering end users' affordability and willingness to pay operators either need to reduce the generation cost or source some tariff subsidies. A long-term tariff subsidy may not be ideal for mass diffusion of this off-grid electrification approach. However, the present study estimated much lower subsidized LCOE (in comparison with the COE from decentralized generations for off-grid areas in many developing countries) for different hybrid combinations at different locations in chapter-4, which have been summarized below (Table 5.2). These hybrid mini-grid systems are optimized with the RE resources availability and local load profiles. All these selected systems represent 78% to 100% renewable energy share.

Hybrid combination	Genset capacity	RET capacity	RE share	LCOE* (USD/kWh)	Break-even point
100% diesel	30KVA	-	0%	0.538	-
Hybrid PV	20KVA	60kW	93%	0.456	12.7 years
Hybrid small wind	20KVA	60kW	83%	0.451	11.2 years
PV-small wind	10KVA	PV 35kW, W20kW	91%	0.420	8.7 years
Hybrid small hydro	10KVA	26.8kW	97%	0.219	1.5 years

*LCOE estimated as RE components market price in 2011

Table 5.1: Estimated cost of electricity and project break-even point for different hybrid combinations (Source: ARE, 2012)

A common capital subsidy of around 40 percent has been applied in all proposed hybrid systems (excluding Rice Husk project). The proposed area specific hybrid combinations of mini-grids are able to supply electricity between USD 0.172 to USD 0.308/kWh (Table 5.2). The rice husk-diesel hybrid system in Rangpur offers the cheapest COE, as this system does not use any battery backup and the diesel generator is very rarely utilized. Micro hydro-PV mini-grid in Mainemukh delivers cheaper unit cost of electricity if the project is used for serving wider load. Among the Wind-PV-diesel hybrid systems Chakaria mini-grid serving bigger load of 366kWh/day for 18 hours offers the most competitive COE (USD 0.217/kWh).

HMG system	Load served (Kwh/d)	Initial capital (USD)	Operating Cost (USD)	NPC (USD)	LCOE (USD/ kWh)	Serving Duration (Hours)	Reference (*In this research*)
Rangpur *Husk-Diesel*	328	85,000	12,345	174,567	0.172	12	Table 4.6a
Mainemukh *Micro hydro-PV*	32.4 44.97	44,700 44,700	1,321 1,321	61,783 61,783	0.404* 0.291	6 13	Table 4.8
Naogao *Wind-PV*	366	231,000	13,166	401,120	0.248	18	Table 4.9
Chakaria *Wind-PV*	366	162,000	13,641	332,000	0.217	18	Table 4.9
Naogao *PV-diesel*	366	132,000	29,087	464,030	0.308	12	Figure 4.19d
Coastal *PV-diesel*	176.77	58,000	13,387	231,000	0.316	16	Table 4.13
Coastal *Wind-PV-diesel*	176.77	65,000	12,609	287,000	0.290	16	Table 4.13

* Requires tariff subsidy

Table 5.2: Details of proposed optimum hybrid mini-grids for Bangladesh

It is evident from the different hybrid mini-grids performance analysis in chapter-4, that the same size system can offer much better techno-economic performance while serving a wide spread load rather than the same load concentrated over fewer hours. Considering the results of the field survey, the off-grid rural and remote load profiles can be spread over longer hours through consultation with the consumers although the total load requirement remains relatively small.

5.10 Business Models in practice

The most comprehensive business models study so far for the developing countries has been carried out by the ‘Alliance for the Rural Electrification’. This study identified four major business models that have been applied by many countries in the recent years (ARE, 2012).

5.10.1 Community based model: In remote and isolated areas where mini-grids do not attract any private investment this model enables small projects being operated by the local communities to run. Projects are mostly installed by the government utilities or by local authorities as fully (or up to 80% in some cases) subsidized or donor-funded. The tariff structure is mainly 'flat-fee based' to cover operation and maintenance cost.

There are some small mini-grids in Latin America owned by co-operatives and some medium sized ones have public-cooperative ownership (World Bank, 2007). In China many micro-grids are owned by 'village committees' (UNDP, 2005).

5.10.2 Private sector based model: There are around 700 mini-grids run by private investors (ESPMAP, 2008). These projects have different levels of subsidies and incentives. A tariff subsidy based private ownership has been running in the Philippines and such transition has been shown in figure-5.4. Under this model private investors are selected according to competitive true generation cost of electricity. The public sector decides the retail electricity price, which is generally lower than the generation cost. The government subsidizes the difference to support the private operator.

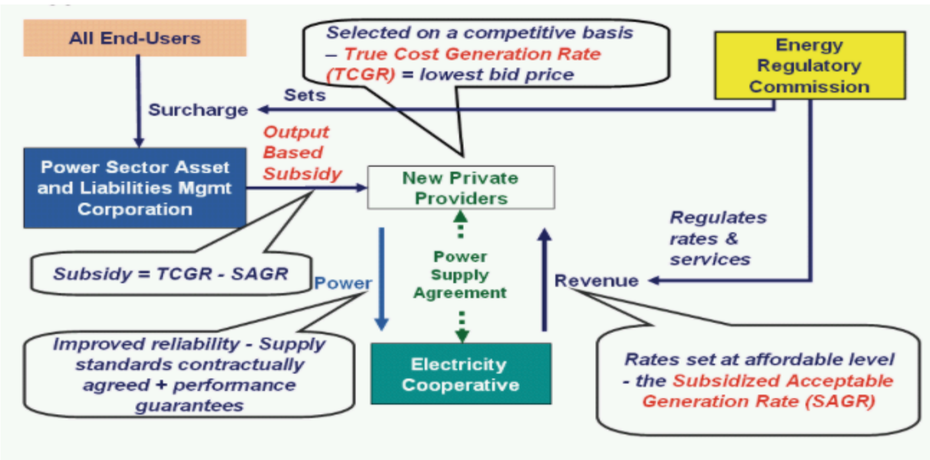


Figure 5.4: Philippines off-grid generation: structure of PPP transaction (*Courtesy: Castalia Consulting*, USA; Source ARE, 2012)

The output-based subsidies make such models viable in real time operation. As the public utility oversees the operation and maintenance activities, service level assumed to be very good.

5.10.3 Utility based model: Utilities are the most common actors owning mini-grids in developing countries (World Bank, 2008). The most crucial benefit of this model are the economies of scope to achieve privileged administrative and legal edge. However, conventional utilities need more innovative approaches to get better success. Tunisia, Morocco and Thailand have followed this model.

5.10.4 Hybrid business model: This approach combines two or more business models to obtain the optimum sustainability. For example, a state-owned utility provides funding for a mini-grid project and private investor implement it and hand it over to one or more cooperatives for smooth operations. The Salla 650kWp Solar project (under construction) in Sunamganj, Bangladesh is an example of such a model. This project will be funded by BPDB under the Climate Change Trust Fund (CCTF) and will be implemented by private investor on a turnkey basis (BPDB, 2008). Finally BPDB will run the project under different cooperatives.

5.10.5 Other business models: Palit and Sarangi (2014) reported two successful business delivery models in India:

1. *Service delivery model:* Under the VESP (Village Energy Security Program) and RVEP (Remote Village Electrification Program) supervision communities run the operations and maintenance of the projects.

2. *Community engagement model*: WBREDA (West Bengal Renewable Energy Development Agency) and CREDA (Chhattisgarh Renewable Energy Development Agency) own and run the mini-grid projects. However, they involve local communities in different management initiatives, like revenue collection etc.

Bhattacharyya (2014) identified the journey of Husk Power System India from BOOM business delivery model to BM model. This private company adopted itself with the appropriate business models in the course of time (Figure 5.5).

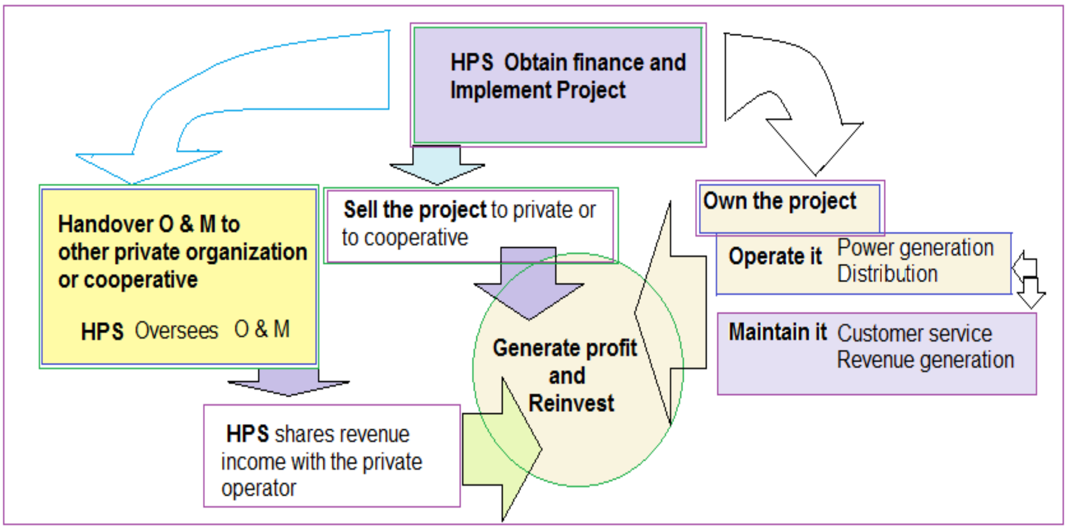


Figure 5.5: Different business models adopted by HPS (Source: Author)

On the other hand the European utility giant E.ON made its move to the rural Tanzanian off-grid market as a rural utility with their standard containerized PV-battery RE energy pack solution (Figure 5.6). Branding its business as 'Rafiki Power' (RF) E.ON applied the BOOM model. Rafiki Power builds standard hybrid systems in 20 feet containers and installs them in off-grid location after an intensive customer survey. RF has applied different innovative approaches for its project's success. Use of drones in remote areas for site survey and mobile credit to up for electricity made it cost efficient. E.ON emphasizes on income generation of local poor using electricity, customer education and integration and finally capacity building.

Figure 5.6: E.ON's Rafiki Power PV-battery hybrid system in rural Tanzania (Source: eon.com)

5.11 Business model for Bangladesh

A business model incorporates associated investment, long term financing, business strategy, project implementation and management. Decentralized renewable mini-grids are not widely anticipated as business ventures for private sectors. However, there are some public, private and public-private ventures in many developing countries. Some distributed mini-grids in Bangladesh and other countries and their commercial structure and techno-economic performances have been discussed earlier in this chapter. In the light of the discussion the proposed mini-grids for Bangladesh (Table 5.2) can be commercially implemented under two general business models:

1. Ownership model
2. Service delivery model

However, considering the investment opportunities and barriers (as stated earlier in this section) proposed mini-grid should have a hybrid business model and consider the following issues:

1. Type, nature and scale of service required
2. Size of the project
3. Market (consumer) condition
4. Policy environment

Prior to exploring the business delivery model a crucial *private investment suitability* assessment has been carried out by applying the 'sustainability indicator checklist' based on the primary and secondary data analysed and results obtained from this research work (Table 5.2a). The positive sustainability indicators against each key element support the private investment initiatives in decentralized hybrid mini-grid electrification in Bangladesh. Investors can carry out simple financial analysis to forecast the revenue earning and profit generation from the proposed hybrid projects by estimating the net profit from the sales revenue earned over the project life to justify the business model. For example, the proposed Chakaria Wind-PV hybrid project delivers levelized COE at USD 0.217/kWh while serving a 366kWh/day wide spread load of 18hours a day (Table 4.9). Considering actual electricity supply at 90% of load demand and estimated (minimum) average retail unit price as USD 0.35 (Table 5.2b), this project can make an estimated net profit of USD 348,650 over its lifetime (20yrs).

Moreover, if private investors engage in this field on a large scale (multiple projects), claiming the carbon credit can help to recover the cost of the project in a better way. In the case of small scale engagement government should take the responsibility to claim the carbon fund. On the other hand, government can increase the amount of initial subsidy to attract more investment and subsequently offset its expenditure by claiming the carbon credit under a mutual agreement with the private investors.

Sustainability indicator	Yes	No	Explanations
Resources and Hybrid systems			
1. Can a proposed hybrid system be optimized?	✓	✗	All the proposed HMGs (table 5.2) are optimized for the applicable RE resources, components and load demands.
2. Can the optimized hybrid system be standardized?	✓	✗	Optimized HMGs component share (RE ratio), technology mix and system size can be standardized.
3. Can a standardized system be replicated?	✓	✗	Proposed systems can be replicated in areas with similar RE resources and load demand.
Market			
4. Is the market ready to accept the techno-economic approach?	✓	✗	Based on the data of the field study customers are willing to switch (Table 3.7 & 3.8) and their willingness to pay for this service (Table 3.11 & Table 3.13) supports the proposed retail tariff (Table 5.2b) for private investor.
5. Is the demand bid enough for commercial viability	✓	✗	Although individual load is poor but total combined load supports a system's viability (Table 3.9 & 3.9a).
Institutions			
6. Does the policy support suitable for project financing?	✓	✗	'The Renewable Energy Polity 2008' supports and encourages private investment, as the objective of this policy is to attract private investment in mini-grids for rural electrification.
7. Any major investment barrier?	✗	✓	Policy supports private investment and efforts given to eliminate any barrier. However, complex licencing process remains as a barrier. Moreover, public and private lenders are neither familiar with such business ventures nor obliged by the policy instrument to support this field.

8. Enough investment opportunities?	✓	✗	Investment subsidies, tax holiday on income, assistance in project site acquiring, customer connection subsidy, IDCOL RE investment fund and tariff subsidy (exceptional cases) etc. offered by the policy.
9. Any major risk or uncertainties?	✓	✗	Natural disasters (heavy flood, hurricane etc.) and grid interventions pose serious threat.

Table 5.2a: Private investment possibility check list

Table-5.2a clearly indicates that private investment has a very good opportunity to step in to this sector in Bangladesh. However, natural disaster and grid intervention issues need to be addressed. An efficient public-private disaster management policy can help overcome this situation. Appropriate policy guideline is required to prevent any undue grid intervention. However, identifying a suitable business delivery model for Bangladesh still remains as a key avenue to investigate. As described in the methodology public, private and cooperative business engagement stages of various models have been checked against all the related actors and elements by applying ranking scores (Table 5.2b). Business engagement levels (build, own, operate, maintain, transfer) for public, private and cooperative associations have been scored and ranked (Tables 5.2c-5.2e) and finally the top scoring business models that are suitable for Bangladesh have been presented in Table 5.2f. Existing policy framework, present status of technical knowhow and stakeholders' views were considered while allocating points against each actor.

Engagement	Elements and actors to be satisfied	Ranking score
Build	Technical capability	
	Access to finance	High = 3
Own	Organizational capability and stability	Medium= 2
Operate	Sustainable generation and operation capability	Low= 1
Maintain	Maintenance capability	Not at all= 0
Transfer	Legal acceptability	

Table 5.2b: Various engagement levels against the elements and actors and allocated ranking scores

Engagement	Elements and actors to satisfy	Score
Build	Do the public sector utilities/ participants have enough technical capability to implement RE resource oriented and area specific hybrid mini-grids? If yes what level?	
	1. Access to resource data and technical knowhow?	3
	2. Project optimization?	2
	3. Resource-Load based cost efficiency?	1
	Do the public sector utilities/ participants have enough resources or access to sufficient financing/ funding?	
	1. Subsidies/ donation?	
	2. Equity?	3
	3. Loan finance?	3
		3
Own	Do public sector utilities/ participants have enough organizational capability and stability to own the project for its lifetime?	2
Operate	Do public sector utilities/ participants have enough technical and human resources and legal flexibility to operate the project sustainably?	
	1. Legal flexibility to set sustainable tariff?	1
	2. Enough revenue collection through tariff?	0
	3. Keep the project running at an optimum technical level?	2
Maintain	Do public sector utilities/ participants have enough resources, experience and capability to maintain the project?	
	1. Access to fund for regular repair and maintenance?	2
	2. Access to fund for unexpected repair and maintenance?	2
	3. Ability to maintain customer satisfaction?	2
Transfer	Do public sector utilities/ participants have legal flexibility and organizational capability to transfer the project to third party?	
	1. To sell the project?	3
	2. To handover to private / community for O & M?	3
	Maximum possible score 45 and Public sector achieved total score of 32	

Table 5.2c: Public sector (utility) engaged business model suitability scorecard

Engagement	Elements and actors to satisfy	Score
Build	Do the private sector utilities/ participants have enough technical capability to implement RE resource oriented and area specific hybrid mini-grids? If yes what level?	
	4. Access to resource data and technical knowhow?	3
	5. Project optimization?	2
	6. Resource-Load based cost efficiency?	3
	Do the private sector utilities/ participants have enough resources or access to sufficient financing/ funding? If yes what level?	
	1. Subsidies/ donation?	
	2. Equity?	3
	3. Loan finance?	3
		3

Own	Do private sector utilities/ participants have enough organizational capability and stability to own the project for its lifetime?	3
Operate	Do private sector utilities/ participants have enough technical and human resources and legal flexibility to operate the project sustainably? If yes at what level?	
	4. Legal flexibility to set sustainable tariff?	3
	5. Enough revenue collection through tariff?	3
	6. Keep the project running at an optimum technical level?	3
Maintain	Do private sector utilities/ participants have enough resources, experience and capability to maintain the project?	
	4. Access to fund for regular repair and maintenance?	3
	5. Access to fund for unexpected repair and maintenance?	2
	6. Ability to maintain customer satisfaction?	3
Transfer	Do private sector utilities/ participants have legal flexibility and organizational capability to transfer the project to third party?	
	3. To sell the project?	2
	4. To handover to private / community for O & M?	2
Maximum possible score 45 and Private sector achieved total score of 41		

Table 5.2d: Private sector (utility) engaged business model suitability scorecard

Engagement	Elements and actors to satisfy	Score
Build	Do the cooperatives have enough technical capability to implement RE resource oriented and area specific hybrid mini-grids? If yes what level?	
	7. Access to resource data and technical knowhow?	
	8. Project optimization?	1
	9. Resource-Load based cost efficiency?	1
		2
	Do the cooperatives have enough resources or access to sufficient financing/ funding? If yes what level?	
	4. Subsidies/ donation?	2
	5. Equity?	1
	6. Loan finance?	1
Own	Do the cooperatives have enough organizational capability and stability to own the project for its lifetime?	1
Operate	Do the cooperatives have enough technical and human resources and legal flexibility to operate the project sustainably? If yes at what level?	
	7. Legal flexibility to set sustainable tariff?	
	8. Enough revenue collection through tariff?	3
	9. Keep the project running at an optimum technical level?	3
		1
Maintain	Do the cooperatives have enough resources, experience and capability to maintain the project?	
	7. Access to fund for regular repair and maintenance?	1
	8. Access to fund for unexpected repair and maintenance?	1
	9. Ability to maintain customer satisfaction?	2
Transfer	Do the cooperatives have legal flexibility and organizational capability to	0

transfer the project to third party?

5. To sell the project?
6. To handover to private / community for O & M?

Maximum possible score 45 and Cooperative sector achieved total score of 20

Table 5.2e: Cooperative engaged business model suitability scorecard

Engagement	Maximum Possible Score	Public	Private (Developer)	Community/ Cooperative	Private (Third Party)
		Points awarded			Not applicable
Build	18	**15**	**17**	8	
Own	3	2	**3**	1	
Operate	9	3	**9**	**7**	
Maintain	9	6	**8**	4	
Transfer/ Sell	6	**6**	**4**	0	
Total	45	32	39	20	

Green: Best combination; **Yellow:** Better combination; **Purple:** Good combination

Table 5.2f: Business model scorecard

From the above findings the sustainable private sector involved business models can be ranked as below:

Best:	Private investor: Build→Own→Operate→Maintain
Better:	Public-Private: Public Build→Public Own→Private Operate→Private Maintain
Good:	Public-Cooperative: Public Build→Public Own→Cooperative Operate→Public Maintain

5.12 Private investment and mini-grid business model

Although mini-grid implementation in many developing countries by public utilities and private investors has been reported to have some successful cases, the scaling up issues are yet to be resolved. The barriers identified in this case are mainly the constraints in designing innovative-effective business models and investment tools. Decentralized mini-grids being very much area specific involves a wider range of service criteria along with variety of technology applications. Therefore, risk profiles related to finance vary with the nature of the project. However, in many developing countries access to commercial financing faces challenges of associated risks along with insufficient market capital

It is the primary responsibility of government to attract private and institutional investments by adopting an appropriate investment friendly policy framework to make a huge impact in this field. However, both the public and private sector should take the initiative to bridge the existing gaps in different aspects of the renewable hybrid mini-grid implications using their own elements of responsibilities (Fig. 5.7).

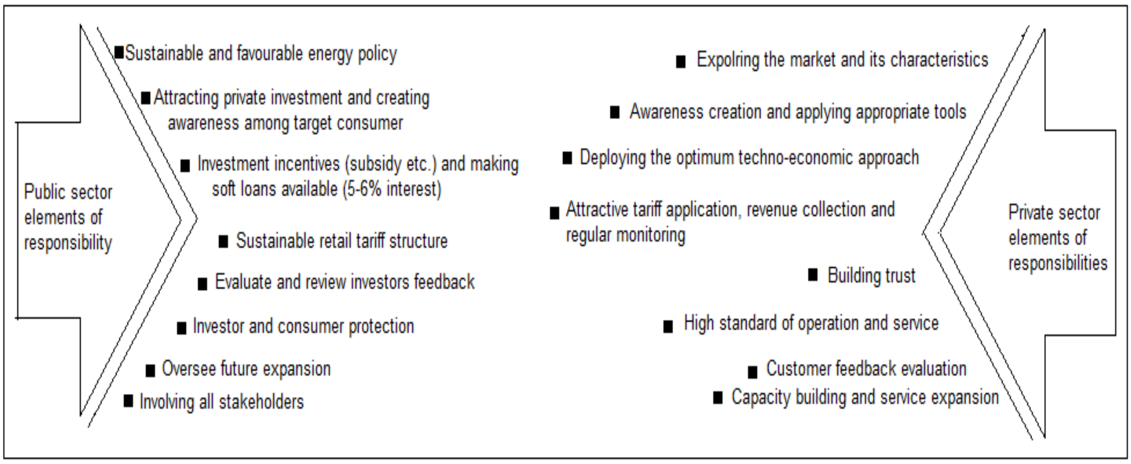


Figure 5.7: Public and private sector responsibilities (Source: Author)

Although, business delivery models for small RE projects deployment in Bangladesh and neighbouring countries are likely to be the same because of prevailing similar socio-economic characteristic (Fig. 5.8), the proposed business model in this research work does not have complete similarities with any of these models.

Country	Technology applied	Business model adopted
Bangladesh	SHS	Consumer finance, leasing
Nepal	SHS, micro/mini hydro	Consumer finance, village energy committee
India	SHS, solar lantern, micro/ mini hydro, Biomass gasifier	Consumer finance, leasing, fee for service, Village energy committee
Sri Lanka	SHS, micro/mini hydro	Consumer financing, village development committee

Figure 5.8: Type of off-grid electrification and business models adopted in South Asian countries (Source: Palit and Chaurey, 2011)

Business models in Figure 5.8, operating in different countries have had very limited success in attracting private investment for mini/micro-grid deployment. Most of the projects are heavily or completely subsidized by government or donor agencies and some of these required recurring tariff subsidies.

Considering the BOOM model solely applied by the private sector as identified earlier (in section 5.11) the private investor has to follow an organized business plan to deliver the business model successfully.

5.13 Business plan to deliver the proposed model

A successful 'business delivery model' is an integral part of the total business plan. There are very limited research works and data available regarding the complete business plan for decentralized mini-grids covering all the aspects, i.e. techno-economic design, sustainable financing tools, income-expenditure analysis, project suitability for private investors etc. In the light of this research work considering all the findings a detailed business plan for the successful commercial deployment of renewable mini-grid business delivery model has been advised here including all related aspects step by step (Fig. 5.9)

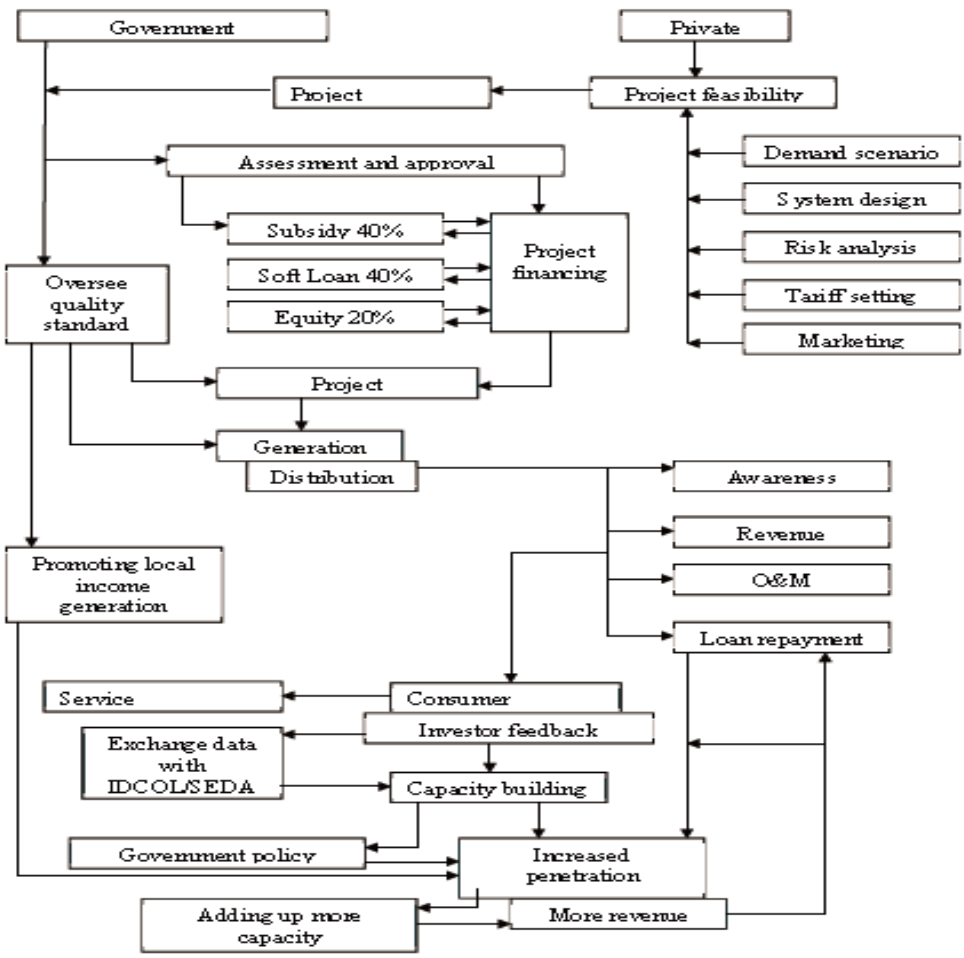


Figure 5.9: Schematic diagram of the proposed business plan implementation (Source: Author)

5.13.1 Location selection: Selection of location is vital for the success of the proposed project. At the initial stage of dissemination of decentralized renewable hybrid mini-grid (HMG) emphasis need to be given by locating projects with in the areas identified as highly prioritized by the government. List of these areas (Fig. 5.10) declared in the government gazette (*Reg. no. DA-1, dated July 26, 2007, as an extension of the renewable energy policy in the Remote Area Power Supply System (RAPSS)*). Nevertheless, private investment is always encouraged in the RAPSS policy if any other off-grid area(s) is potentially suitable for hybrid mini-grid development. However, the project area to be covered under the service agreement should be carefully determined, as unnecessarily wider distribution network may involve in excessive investment and distribution loss may be higher as well.

Areas selected by the government for development of RAPSS

1) Patgram
2) Hatiabandha
3) Roamari
4) Rajibpur
5) Madarganj
6) Kalmakanda
7) Khaliajuri
8) Tahirpur
9) Dharampasha
10) Sullah
11) Itna
12) Mithamain
13) Astagram
14) Debhata
15) Assasuni
16) Kaliganj
17) Lohagara
18) Kalia
19) Rampal
20) Mongla
21) Mehendiganj
22) Dasmina
23) Galachipa
24) Kalapara
25) Bhola
26) Hatiya
27) Sandwip
28) Kutubdia
29) Maheskhali
30) Teknaf

Figure 5.10: RAPSS priority areas selected in the renewable energy policy

Prior to making any investment, investors need to be sure that natural resources data (i.e., solar radiation, wind data, water height of canal, biomass availability etc.) are available for the proposed area. A hybrid system should never be designed and implemented based on any assumed data.

Electricity demand assessment needs to be carried out at the initial stage of site selection. Investor should consider the area for min-grid operation only if there is enough primary load demand prevails for the operation of the project. Moreover, various load demand throughout the day and all-round the different seasons need to be studied for planning the right hybrid system size and determining the share of resources to be applied.

5.13.2 Business strategy: A pre-investment business strategy needs to include the market analysis, penetration plan, stakeholder involvement technique, customer awareness creation, future expansion plan, perceived risk analysis and mitigation and sustainable operation and maintenance.

Investors need be aware that not every single household in the project area would be their customer in the first place. Therefore, a pre-project survey has to be carried out to find the probable number of customers in the proposed area. This will give a clear picture of load demand. A rapid increase in penetration rate can be planned for the first five years. A 40%–50% increase in customer base in five-year time would help the project to run successfully. Therefore, a project expansion plan (increase the capacity of a single project) has to be in place in line with the target penetration rate. The renewable energy policy states that ‘an allocated RAPSS area should preferably be contiguous and include the entire area of two or more Upazilas’. Therefore, investors could take the opportunity to go for multiple project areas gradually to enhance the profitability. For example, an investor investing in Kutubdia (Fig. 5.10) can consider extending its investment area in the neighbouring island of Moheskhali (Fig. 5.10), as the socio-economic conditions and abundance of resources in these two islands are similar.

Stakeholder involvement is essential for the success of the project. Local administrative authorities, consumers, other people living in the area, businesses and any other institutions (i.e. school, health centre etc.) need to be the part of the business strategy. This is very important to reduce any socio-cultural uncertainties and especially to fight against electricity theft.

Having in-depth stakeholder involvement in a wider area with multiple projects from the same investor will help in cost efficient sustainable operation and maintenance.

5.13.3 Project financing: According to the latest renewable energy policy, government may provide a subsidy up to 60% of the generation plant only. No subsidy provision has been introduced for the distribution network. In the earlier section of this research work it was shown that a 25% to 40% subsidy of the total project cost help to reduce the cost of electricity generation and offer a better project NPC. However, a 60% subsidy (as in the policy) in the project generation plant investment will help to introduce even better tariff to the consumers, as the amount of subsidy would exceed the fixed cost of distribution network etc. For example, for the 80kW hybrid system in Naogao initial investment by the private investor amounts to USD 286,000 with a 26% subsidy on the total cost (Fig. 4.11, 4.12 and 4.13), where the subsidy (USD 100,000) covers the whole cost of distribution network. Having a 60% subsidy on the generation plant only for same project, the private investor needs to invest total of USD 224,000 (USD 114,000 as 60% *subsidized* + USD 100,000 *as other cost*) instead of USD 286,000. In practice the maximum subsidy (60%) may not always be offered. However, the private investor can negotiate the best possible option for their first few projects with the government.

Depending on the range of subsidies offered by the government in the renewable energy policy, subsidies applied in mini-grid projects (PV-Diesel mini-grid in Sandwip, Rice-husk project Kapasia) and subsidies applied proposed hybrid systems in this research (Table 5.2) financing structure could be of as follows:

40% subsidy 40% soft loan and 20% equity
50% subsidy 30% soft loan and 20% equity

To establish mini-grids as a successful business, the maximum subsidy may be offered for the first few projects along with the least possible interest rate (5% to 6%) on the loan. Once the diffusion of decentralized electrification through private investment reaches a level where economies of scale can be achieved, the subsidy can be reduced or eventually be eliminated.

At present loans are not widely available in this sector because of the nature of the business as discussed earlier. Government should encourage public and private banks, other financial institutions and lenders to create especial funds available for the RAPSS investors by applying the appropriate policy instrument. To attract more private investment, interest on the investment and the repayment could be frozen for the first one or two year so that a project can go into full scale operation and pay back from the income generated.

5.13.4 System design: Hybrid system design including the capacity and renewable resources mix has to be carefully carried out considering demand and availability. The designed system should neither be over-sized to minimize the cost nor be under sized to avoid consumer dissatisfaction. However, the system should have the provision to add more capacity to meet future demand. Replication of hybrid mini-grid systems is more likely possible in the same extended geographical areas. For example, if a private investor implement a hybrid project of 100kW having 60% wind, 35% solar and 5% diesel combination in a part of Kutubdia (RAPSS area no. 28; Fig. 5.10), the same project design can be replicated in the same area and in the adjacent island Moheskhali (RAPSS area no. 29; Fig. 5.10).

5.13.5 Tariff setup: The rural market study carried out for this research work explores the whole horizon of mini-grid target consumers' affordability and willingness to pay for the electricity to be supplied by the proposed mini-grids. Depending on the hybrid mini-grid's actual generation cost the retail price can vary as (Table 5.2g).

HMG system	LCOE(USD/ kWh)	Serving Hours	Reference *(In this research)*	Suggested retail price of electricity (kwh)*
Rangpur *Husk-Diesel*	0.172	12	Table 4.6a	*USD 0.25 – 0.30*
Mainemukh *Micro hydro-PV*	0.404**	6	Table 4.8	*USD 0.4+*****
	0.291	13		*USD 0.35 – 0.40*
Naogao *Wind-PV*	0.248	18	Table 4.9	*USD 0.30 – 0.35*
Chakaria *Wind-PV*	0.217	18	Table 4.9	*USD 0.30 – 0.35*
Naogao *PV-diesel*	0.308	12	Figure 4.19d	*USD 0.35 – 0.40*
Coastal *PV-diesel*	0.316	16	Table 4.13	*USD 0.35 – 0.40*
Coastal *Wind-PV-diesel*	0.290	16	Table 4.13	*USD 0.35 – 0.40*

* Retail price range for unit electricity suggested on the basis of customer maximum WTP value
** Requires tariff subsidy

Table 5.2g: Hybrid mini-grids possible price reference points

The project owner can decide a well-accepted retail tariff as suggested in table-5.2a. Rural customers are willing to pay a maximum USD 0.43/kWh (Table 3.13). A smart pricing strategy should be adopted to serve all the income levels.

5.13.6 Connecting end users and revenue collection: Depending on the various demand type and affordability of the consumer different types of connections need to be designed in practice. An 80kW plant serving 200 residential customers may not have the same load demand in every household. Based on the market survey (Chapter 3; Table 3.2 &3.9b), five different types of residential consumers could be envisaged by connecting them to the mini-grid as below:

User type	Residential market share	Consumption range
Bottom user	17.33%	3 – 5 kWh/month
Basic user	22.33%	5 – 13 kWh/month
Medium user	40.00%	13 – 20 kWh/month
Large user	12.67%	20 – 25 kWh/month
Large plus user	7.67%	23 – 28 kWh/month

Table 5.3: Proposed mini-grid customer connection type

The identified range of customers (Table 5.3) corresponds to the IEA, World Bank Multi Tier Customer Framework of electricity service for rural households. (IEA, World Bank, 2014). For the *Bottom* and *Basic users* a fixed monthly/ weekly charge for usages can be applied. On the other hand *Medium*, *Large* and *Large* plus users can be connected with pre-pay or post-pay meters depending on their financial conditions. For commercial usages, i.e., shops, cottage factories etc, a fixed charge can be applied or be fitted with meters on a '*pay as you go*' basis. However, consumer income frequency (Table 3.2) needs to be considered to decide their payment type. For example, a *Large user* having only seasonal income could be offered a prepay connection to avoid any unexpected non-payment issue.

Regarding the connection fee of USD 38.60, a major part of the Bottom and Basic users are not willing to pay any amount (Table 3.10). Private investor can negotiate with IDCOL to obtain a connection fee subsidy for the lower income consumers. However, the customers willing to pay this fee could be offered a flexible instalment for wider acceptance of the mini-grid electrification approach.

Consumers need to be educated both by the public and private sector for effective and productive use of electricity. Thus social empowerment can be achieved through income generation, which in turn will help mass diffusion of renewable mini grids.

5.13.7 Operation and maintenance: A smooth operation and maintenance procedure is essential for any successful business. Unlike the business delivery models cited in figure 5.8, this research would suggest that investors have full control and responsibility for the operation and maintenance of the plant. However, the local community need to be integrated into the business plan, as any business venture at the bottom of the pyramid requires the consumers moral association with it. For smart operation, cloud based remote data monitoring system can be applied for a number of projects in the same geographical areas. Project manager(s) or operators need to maintain regular interactions with the local member of the public for better understanding of consumer need. Local youths can be trained as skilled manpower to be employed in future project expansion and thus capacity building will be achieved.

Timely maintenance of all equipment is very important for providing reliable service and acquiring consumer confidence and loyalty. Any operation and maintenance has to be in accordance with the IDCOL's standard policy guideline. For example, replacing any component, i.e., solar panel, battery, battery chemical etc. and disposal off should follow the quality standard and environmental policy guidance laid out by IDCOL.

Everyday operational data and resources abundance need to be duly collected and preserved, as this would help both the private investor itself and the policy makers to step forward in mass penetration in this market.

5.13.8 Monitoring and Customer feedback evaluation: Monitoring the project operation (i.e., load matching), business activities (i.e., revenue collection) and customer feedback (i.e., quality of service) analysis is the key to growth. Reliable service will result in positive customer attitude towards this electrification approach and finally will help to achieve more penetration.

5.13.9 Reinvesting and growing with innovative business model: Private investor should have a plan to reinvest from the revenue income in to mini-grid business expansion to new locations. Replicating the hybrid systems in new areas will open the opportunity to decentralize its operation and maintenance to other private investor or local cooperative. Thus a private investor can become technology consultant to sell tailor made (regarding RE selection and size) hybrid systems.

5.14 Scaling up:

Decentralized hybrid mini-grid designs have been standardized in the earlier part (Chapter 4) of this research for different areas based on available renewable resources while employing the resource map constructed for this purpose (Figure 2.8; Chapter 2). The suggested optimum systems (Table 5.2) can cover whole off-grid areas of the country. While applying the most suitable ***Private Sector BOOM business model*** (section 5.11) identified in this research work private investor can replicate the suggested optimized hybrid system combinations (Table 5.2) and thus scaling up of this approach can be achieved.

5.15 Conclusions:

As there is huge identified demand of electricity in the remote rural areas and significant un-quantified demand as well, a combination of suitable policy framework and its proper implementation with an investment friendly socio-political environment will attract the required investment in this field. The business models advised in this section and the simple financial analysis indicate the scope for private investors to invest on a large scale in the hybrid mini-grid sector.

The optimal hybrid system configurations obtained from this study indicate that cost-effective hybrid mini-grids can be developed for decentralized electricity supply in the off-grid areas of Bangladesh. However, an efficient revenue recovery strategy is important to ensure project sustainability. Consumers in the mini grid area could be categorized depending on their need and financial capability. For the basic users, a fixed monthly/ weekly charge for usages can be applied. On the other hand medium and large users can be connected with pre-pay or post-pay meters depending on their financial conditions. For commercial usages, *i.e.*, shops, cottage factories *etc.*, a fixed charge can be applied or be fitted with meters as "*pay as you go*" basis.

Smart pricing of electricity is essential, which sets different price for different hours of the day and night depending on the cost of production. Time varying pricing scheme (Kimera, et al., 2012) can be a very effective tool for influencing the price responsive end users. "Seasonal tariff set up" is another option to recover the cost of production with varying availability of resources in specific project locations. For agricultural activities, a subsidized tariff may be required, as farmers use highly subsidized diesel for irrigation in Bangladesh. In this case private electricity suppliers may request for an extended "*tariff subsidy*" for agricultural activities and receive support from the government.

Successful implementation and operation of decentralized renewable hybrid mini-grid in Bangladesh can be achieved by following the suggestions made out of findings of this research work. However, the governments' policy environment and the political commitment will play the most important role in mass diffusion of this approach.

Chapter 6

Research Findings-
Off-grid electrification through renewable hybrid mini-grid: not a dream anymore

Chapter Highlights

This chapter presents the key findings of this research work and its contribution along with some important policy recommendations and scope for further research.

Chapter 6

Research Findings- 'Off-grid electrification through renewable hybrid mini-grid: not a dream anymore'

6.1 Research Findings

The Bangladesh governments' target of *electricity for all by 2021* still remains an unrealistic destination for the nation. The country's energy situation in a global context justifies the demand for off-grid electrification through decentralized renewable mini-grids (see chapter 1). Bangladesh is endowed with an abundance of renewable resources, which can be applied for electricity generation from decentralized mini-grids. The resources map developed for this research work (Figure 2.8), which gathered all available renewable resource data, helps to choose area specific resources for proposed mini-grids.

Collected field data revealed that a young age group (31-40 years) dominates in decision making in case of switching from current fossil fuel based lighting to renewable mini-grid (RMG) based electrification (Table 3.1). This comparatively advanced age group expressed their clear interest to get electricity from RMG as the mean value of willingness to switch (WTS) ranges from 3.67 to 4.86 for RMG across all income groups (Table 3.7). Current usages of kerosene, expected load demand and estimated expenditure for electricity from RMG across all income groups show that consumers can save cost while using electricity even for longer hours and different purposes (Table 6.1).

Detailed off-grid village level load demand data were collected to explore the domestic, commercial and agricultural load in the study areas. At the same time data were also collected to explore customers' willingness to pay (WTP) for the electricity from the proposed renewable hybrid mini-grids. Such approach of collecting field data is first time ever in Bangladesh. Collected data and their further analyses helped in designing the optimum hybrid systems using the HOMER micro-grid modelling software.

User category	Income level (USD/month)*	Min & Max load demand (kWh/month)	Cost range** (USD/month)	Present cost of Kerosene (USD/month)
Bottom	> 50	3 - 5	1.2 – 2.0	5.00
Basic	51 - 77	5 - 13	2.0 – 5.2	7.16
Medium	78 - 103	13 - 20	5.2 – 8.0	9.59
Large	104 -128	20 - 25	8.0 – 10	12.95
Large plus	> 128	23 - 28	9.2 – 11.2	11.50

* Income in BDT converted to USD (1 USD = 78Tk)
** Unit cost of electricity estimated as USD 0.40/kWh

Table 6.1: Customer categories and their monthly cost of kerosene, estimated cost of electricity against expected load demand

Design and optimization of area specific various sizes of mini-grids in chapter-4 established the fact that hybrid systems perform better while serving a load designated over longer hours. It was explored during the field data collection that the usual shorter evening loads (4-6 hours) can be spread over longer hours by customer consultations and adding commercial and agricultural loads in the day times can offer wider loads of 12-18 hours a day. Capital subsidies and low cost interest on investments have been proved as necessary tools for lowering the levelized cost of electricity (LCOE), which is essential for early diffusion of the technology.

The entire off-grid areas of the country and all area specific potential renewable energy resources were considered by analysing numerous hybrid models. Some top ranked optimized hybrid renewable mini-grids suggested by HOMER have been analysed in chapter-4 (HMG group 1, 2 & 3) and a comprehensive short list is presented below (Table 6.2). Any particular HMG system from this list can be replicated with minimal adjustment. For example, areas identified with an abundance of rice husk in resource the map (Figure 2.8) can use the 'Rangpur Husk-Diesel' hybrid combination. Similarly areas identified as rich in 'Micro-hydro-Solar' or 'Wind-Solar' or 'Solar' resources can be applied with the corresponding hybrid system combination from the list below (Table 6.2).

Considering the economic features, load management criteria and integrated hybrid system performance these top ranked hybrid systems outperformed all other combinations. In case of different load profile to be served any of the suggested combinations can be recalibrated by the system developer.

HMG System Architectures	Load served (kWh/d)	Initial capital (USD)	Operating Cost (USD/y)	NPC (USD)	LCOE (USD/ kWh)	Serving Duration (Hours)
Rangpur ***Husk-Diesel*** 80kW Gasifier +60kWGenset	328 72kWp	85,000	12,345	174,567	0.172	12
Mainemukh ***Micro hydro-PV*** 40kW PV+ 2x5kW Wind+ 30kW Genset	44.97 12.9kWp	44,700	1,321	61,783	0.291	13
Naogao ***Wind-PV*** 90kWPV+4x10kW Wind+60kW Genset + 288 Batteries	366 79kWp	231,000	13,166	401,120	0.248	18
Chakaria ***Wind-PV*** 60kWPV+10x3.5 kW Wind+60kW Genset + 210 Batteries	366 79kWp	162,000	13,641	332,000	0.217	18
Naogao ***PV-diesel*** 140kWPV+40kW Genset+ 440 Batteries	366 80.5kWp	132,000	29,087	464,030	0.308	12
Coastal ***PV-diesel*** 60kWPV+3xG3+ 30kWGenset+80 Batteries	176.77 38.6kWp	92,000	13,387	231,000	0.316	16

Table 6.2: A comprehensive list of top optimized HMGs

Having the customers' WTP value (WTPmax USD 0.43/kWh) well above the estimated cost of electricity by different hybrid systems (Table 6.2), any project can make a substantial amount of profit to attract private investment.

Different mini-grid business models around the world have been studied along with a few existing projects in Bangladesh to identify the most suitable business model for Bangladesh. Considering the socio-political and policy environment the ***private sector dominating BOOM (Build→Own→Operate→Maintain)*** has been suggested as the most sustainable business model for Bangladesh.

The private investment-friendly renewable energy policy of Bangladesh and the huge demand for electricity at the off-grid 'bottom of the economic pyramid' market can pave the way to mass diffusion of decentralized renewable energy based electrification. However, government should have a firm socio-political commitment for encouraging the private sector to come forward and invest in this field. Eliminating the bureaucratic hindrance in licencing process, access to grant or loan and other administrative activities can enhance this initiative.

Replication and scaling up of such an approach can be achieved by initiating private sector investment following the hybrid system combinations and business model suggested in this research work and thus the economies of scale that can be achieved. Finally the poor people in the off-grid areas of Bangladesh will be able to get an electricity supply from the distributed renewable mini-grids and their lives can be changed. The same approach can be applied in other developing countries to provide electricity for millions of poor people.

6.2 Policy Recommendations

Based on the primary and secondary data analysed and the findings of this research work some major recommendations are made as below:

- Data: Off-grid projects in remote areas face data and information challenges. While project viability requires site-specific analysis, investors may worry about load profile, resource availability and initial costs. So, government could provide essential data and profiles for preferred locations.
- Need for support: Most of the mini-grid projects would need subsidies at least initially. A transparent subsidy mechanism will be helpful.
- Productive tariff subsidy: Special 'tariff subsidies' for farming and small cottage industries can be offered by the government to reach more social empowerment.
- Ensure regulatory certainty: Grid extension is a major risk for any off-grid project and the utility and government could provide a guarantee that no grid extension will take place in 10-15 years or if grid is extended, the investor will be suitably compensated. Politically motivated grid extension needs to be avoided.

- Effective natural disaster recovery management strategy (disaster protective design, insurance, need based aid fund etc.) needs to be included in the policy.

6.3 Contribution of this Research

Detailed survey of 300 off-grid domestic users and 60 business and other entities provided realistic information about the system design parameters. The study has used these data as opposed to assumed data. Willingness to pay (WTP) estimation for mini-grid based electricity supply at the bottom of the pyramid (BOP) market is new in Bangladesh. Coverage of different regions and climatic zones of the country to capture the different resource mix for hybrid mini-grids design and their implementation opened up new horizon of possibilities. The systematic appraisal provides better understanding of the potential of such an electrification approach.

Successful and failed cases of mini-grids in Bangladesh were analysed to learn about them. Comparative analysis with two other cases was also done; this helped identifying the conditions and barriers to the mini-grid business. Business model analysis considered a set of steps to implement the projects. This captures the entire set of processes to ensure viable mini-grid business in Bangladesh.

The findings of this research should help bridge the knowledge gap in decentralized renewable hybrid mini-grid based electrification in the rural and remote areas of Bangladesh. Part of this work already has been published in the *'Energies'* an internationally reputed journal (*see reference: Alam and Bhattacharyya, 2016*) which covers mini-grid based electrification for the coastal areas of Bangladesh. Another three articles covering the '*off-grid market characteristics and electrification potential'*, '*mini-grid based electrification for the rest of the country'* and '*rural electrification: beyond the traditional approach*' are underway. These articles will share the outcome of this research work with the scientists, academics, policy makers and other stakeholders across the world, which will enhance quick dissemination of this technology approach in other nations.

Hybrid mini-grid system designs and suggested business models will help the people in off-grid areas to access reliable and modern electricity in an affordable way and will increase the renewable energy share in the country's energy mix. Thus this research helps in achieving SDG7 for Bangladesh.

6.4 Possible Areas for Further Research

Some potential areas for further research have been identified through this research work. These are briefly presented below:

1. Resource mapping carried out for this work was based on secondary data. However, *use of GIS based resource analysis and resource map development* may help in efficient application of renewable technologies for hybrid mini-grids by integrating other factors (i.e., project site characteristics, seasonal agricultural activities) in this process.

2. This research has identified issues related to lack of sufficient energy demand data in off-grid areas and undue grid interventions in mini-grid project locations. D*eveloping a comprehensive list of potential project sites with relevant data set* will reduce the unforeseen risks and enhance the chances for private investment. Therefore, creating a comprehensive database of potential sites and energy demand is recommended as a future area of study.

3. There are some public and private owned mini-grids in operation in Bangladesh. For the purpose and scope of this study only the current operational data was collected for the first time. However, continuous monitoring of the techno-economic output of such projects will help the policy makers and investors to make informed decision in future projects. Therefore, *the real time study of existing mini-grids to identify the performance issues for future reference* is highly recommended.

4. This research work and all other related works related to decentralized hybrid mini-grids in Bangladesh have considered only the 'kilowatt scale' of systems. However, *investigation of large-scale rural hybrid systems (MW-scale) for 24/7 supply* covering multiple locations is recommended for areas with high demand of electricity.

5. HOMER the widely used simulation software has been used to design mini-grid systems in this research work. While exporting the time-series renewable resource data in to HOMER for analysis, the shortest time step that can be applied is an hour. However, in real life hybrid system components need to be very proactive to response with any changes in RE resources even for a very short period. For, example for an unexpected cloudy sky for a few minutes will affect the PV output and hence the performance of the system. Therefore, investigating *possible effect(s) of "hourly time step" application in HOMER* for renewable resource input is recommended.

6. Considering the scope of this study only lead acid batteries were applied in designing mini-grid energy storage. However, lithium ion or nickel cadmium batteries might be techno-economically more feasible to replace the application of lead acid battery option in Bangladesh. Therefore, *techno-economic analysis of such energy storage options (Lithium Ion, Nickel Cadmium) considering their relative energy densities in hybrid mini-grid systems* is recommended for future research.

7. This research only considered the fixed speed diesel generator(s) to compliment the RE resources in mini-grid designs. Application of variable speed generator can offer better flexibility and stability to a hybrid system. Therefore, *investigation of techno-economic performance of "variable speed diesel generator" in hybrid mini-grid application* is highly recommended.

8. *Application of "bio-diesel generator" in hybrid mini-grid system* can be another avenue for future research.

9. Levelized cost of electricity (LCOE) has been applied in this research for ranking the hybrid mini-grid system's suitability. However, in many cases LCOE do not represent the actual energy consumed by the end users. Therefore, *investigating the Energy Return on Investment (EROI) in different mini-grid scenario* may offer a better insight in this regard. Therefore, study of EROI in particular mini-grid system is recommended for future study.

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Appendix I:

Field data collection instrument (Total 4 pages)

Current status of village electrification, expected load profile scenario and willingness to pay data collection questionnaire

Date: … … …
Respondent Sl. number: … … ….
Respondent name: … … ….
Village Name: … … ….
Age: 25-30□ 31-40□ 41-50□ 51-60□ 61-70□ 70+□
Sex: Male□ Female□
Profession: … …. … (Optional)

(Note: Interviewer to explain the aims, objectives and scope of the study)
Currency conversion (1USD = DBT 78.28)

Sl. No.	Question	Answer
1	Household income per year? Income frequency	TK. ……. (USD ……….) Monthly □ Seasonal □ Both □
2	Do you have any type of access to electricity?	Yes □ (go to Q. 3) No □ (go to Q. 12)
3	What is the source of electricity?	SHS □ (go to Q. 4) Own generator □ (go to Q. 4) Generator connection □ (go to Q. 4)
4	What is the size of the SHS / generator? How long you had it? Your satisfaction level with its performance? (in a Likert scale) Main reason for your answer Your willingness to switch to RMG (in a Likert scale) Main reason for your answer	………. ……Yrs. ….. Months 1□ 2□ 3□ 4□ 5□ … … ... …. … …. 1□ 2□ 3□ 4□ 5□ … …. ….. …..
5	How many light bulbs do you use? For what duration every day and their wattage? (*duration of light bulb/s usages and their wattages to be noted individually*)	1□ 2□ 3□ 4□ Summer: LB1: … w, from …to … : hrs LB2: … w, from …to … : hrs LB3: … w, from …to … : hrs LB4: … w, from …to … : hrs

		Winter: LB1: … w, from …to … : hrs LB2: … w, from …to … : hrs LB3: … w, from …to … : hrs LB4: … w, from …to … : hrs
6	Do you use radio/ HiFi? For what duration every day? Wattage of the equipment	Yes □ No □ … to …. : …. Hrs … … w
7	Do you use mobile charger? How many?	Yes □ No □ … …
8	Do you use a TV? For what duration every day?	Yes □ No □ ………..
9	Do you use electric fan? How many? For what duration every day? (*duration of fan/s usages to be noted individually*)	Yes □ No □ 1□ 2□ 3□ 4□: EF1: ………w, for …… hrs. EF2: ………w, for …… hrs. EF3: ………w, for …… hrs. EF4: ………w, for …… hrs.
10	Do you use any other equipment? If yes, name and wattage of the equipment For what duration every day?	Yes □ No □ 1. ….. 2. ….. …………
11	How much do you spend for electricity per month (as the calculated cost)?	Tk. … … (UDS … …) /month
12	How do you light the household? How many lighting units you use? How many hours every day? Unit 1 Unit 2 Unit 3 Unit 4 Unit 5	Kerosene □ Battery □ Solar lamp □ □ Other … … … 1□ 2□ 3□ 4□ 5□ ….. hrs. ….. hrs. ….. hrs. ….. hrs. ….. hrs.
13	How much you spend a month for this purpose?	Tk. …… (USD .. …)
14	Your satisfaction level with its performance? (in a Likert scale) Main reason for your answer	1□ 2□ 3□ 4□ 5□ … … …. …
15	Would you want to have electricity connection if available? Your willingness to switch to: (in a Likert scale)	Yes □ No □ 1□ 2□ 3□ 4□ 5□

	SHS RMG Main reason for your choice	1□ 2□ 3□ 4□ 5□ … … …. ….
16	How many light bulbs would you like to have? (same wattages) For what duration every day? (*duration of light bulb/s usages to be noted individually*)	1□ 2□ 3□ 4□ Summer: LB1: from …to … : hrs. LB2: from …to … : hrs. LB3: from …to … : hrs. LB4: from …to … : hrs. Winter: LB1: from …to … : hrs. LB2: from …to … : hrs. LB3: from …to … : hrs. LB4: from …to … : hrs.
17	Do you want to use radio/ HiFi? For what duration every day?	Yes □ No □ from …to … : hrs.
18	Do you want to use mobile charger? How many mobile phone(s)?	Yes □ No □ 1□ 2□ 3□
19	Do you want to use a TV? For what duration every day?	Yes □ No □
20	Do you want to use electric fan? How many? For what duration every day? (*duration of fan/s usages to be noted individually*)	Yes □ No □ 1□ 2□ 3□ 4□ EF1: from …to … : hrs. EF2: from …to … : hrs. EF3: from …to … : hrs. EF4: from …to … : hrs.
21	Do you want to use any other appliances? For how many hour(s) every day?	Yes □ No □ …… hrs.
22	If proposed electricity will be supplied at a cost of \$0.40/kWh. Are you willing to accept this cost? (*Compare respondents current unit cost*)	Yes □ No □
23	Considering your intended usages your monthly electricity cost will be …….. Are you willing to accept this cost? (*Cost based on respondent's expected usages*)	Yes □ No □
24	Your willingness to pay for the proposed electricity supply? (USD/kWh) *Note: Please mention the total cost of monthly energy based on estimated load for bid(s) offered*	30□ 40□ 45□ 50□ 55□ 60□
25	Reason for your willingness to switch and pay for the RMG electricity? *Note: respondents can choose more than one*	□Better and more stable energy supply □Clean energy posing no health hazard

	reasons	□More income potential for family welfare □Cost saving in long run
26	For having connection of electricity would you intend to pay a fee of Tk. 3000 (USD 38.6)?	Yes: One off □ Instalment □ No: □
27	Irrigation pump/ Shops etc. 1. What is the daily load requirement? 2. Hours of daily usages? 3. Any seasonal variation?	 .. .. W .. .. Hrs Yes / No If Yes, please add detail

Note: LB: Light Bulb, EF: Electric Fan, SHS: Solar Home System, RMG: Renewable Mini Grid

Ethical issues: The 'ethical approval committee' of the De Montfort University, UK considering all associated ethical issues and conflict of interest issued Approval for field data collection