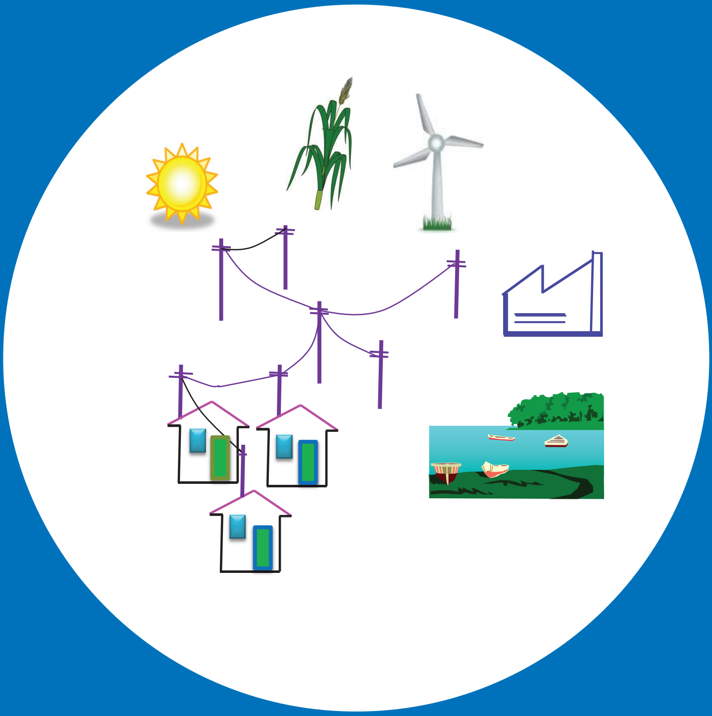
Department of Energy Technology

Accomplishing rural electrification for over a billion people: Approaches towards sustainable solutions

Md. Mizanur Rahman



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Accomplishing rural electrification for over a billion people: Approaches towards sustainable solutions

Md. Mizanur Rahman

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Aalto University
School of Engineering
Department of Energy Technology
Energy Economics and Power Plant Engineering

Supervising professor
Professor Risto Lahdelma

Thesis advisor
Dr. Jukka Paatero

Preliminary examiners
Professor Mark Howells, Department of Energy Technology, Royal Institute of Technology KTH, Stockholm, Sweden

Associate Professor Poul Alberg Østergard
Department of Development and Planning,
The Faculty of Engineering and Science,
Aalborg University, Denmark

Opponents
Professor Esa Vakkilainen, LUT Energy, Sustainable Energy Systems, Lappeenranta University of Technology, Finland

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Abstract

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

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Abstract

Access to electricity appears to be a prerequisite to materialize social, economic, and human development in the underprivileged rural areas. However, 1.1 billion rural people in the world, almost all of them living in developing countries, still do not have access to electricity. Although the rural electrification process poses more challenges than urban electrification, rural areas are blessed with abundant and relatively evenly distributed renewable energy resources. To facilitate electricity access to this huge population, it is essential to deal with the rural electrification task by considering its challenging features and the potential merits of renewable resources. The objective of this thesis is to present policy and techno-economic frameworks for sustainable and accelerated rural electrification for over a billion people in developing countries.

This thesis considers grid expansion as the primary option for rural electrification, and renewable resource based off-grid options were considered as the alternative where grid expansion is not feasible. Grid-based rural electrification policies were examined by focusing on one case program (the Bangladesh rural electrification program) in light of challenges that are generic for developing countries. The assessment of the potentials and techno-economic viability of renewable resources were performed by utilizing analytical methodologies and well-established computer tools (HOMER and RETScreen). The evaluation of choices among rural electrification alternatives has been illustrated with the help of the Stochastic Multicriteria Acceptability Analysis (SMAA) tool. The evaluation methods and tools are illustrated by employing case data obtained mainly from Bangladesh.

This thesis observed that some key policy elements influence the performance of a grid-based rural electrification program. These policy elements guide the rural electrification program towards success through addressing distinct rural electrification challenges. Agricultural residues have the potential to generate electricity to meet household-level demands in rural areas of many developing countries. Hybrid biogas and solar resources can serve both clean-cooking and electricity loads in rural households with achieving benefit (saving) more than the cost. The multicriteria decision support technique enables a rural electrification program to choose decision options from different alternatives based on sustainability criteria.

Keywords Rural electrification, Renewable resource, Multicriteria, Policy elements, Developing country

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Preface

This doctoral work was carried out during the years 2010-2014 at the Energy Economics Research Group (EVO), Department of Energy Technology, Aalto University School of Engineering, Espoo, Finland. I gratefully acknowledge the financial support provided by the Fortum Foundation, the Graduate School for Energy Science and Technology (EST), and the Aalto University School of Engineering Doctoral Program.

I offer my heartiest gratitude to my instructor, Dr. Jukka Paatero, for providing all the necessary supports, ranging from admission to the program, obtaining funding and supporting practical matters to conducting research. I acknowledge his continuous guidance and support throughout my doctoral studies. Without his support, it would not have been possible for me to come to Finland and perform this PhD work. I offer my sincere gratitude to my supervisor, Prof. Risto Lahdelma, for accepting me as a doctoral student and providing me with continuous support throughout the work. Professor Lahdelma's guidance and instructions on publication activities were invaluable to me and significantly enriched my publication experience.

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I would like to thank my dear wife, Suraiya, for her support and my lovely children, Tawsif and Tasfia, for making me euphoric by their presence. Above all, all the praises are due for Allah (God), the creator to Him we all to be returned.

Espoo, February 2014
Md. Mizanur Rahman

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List of publications

This doctor dissertation consists of an overview of the following five scientific publications. The publications are referred to by Roman numerals [I-V].

I Rahman MM, Paatero JV, Poudyal A, Lahdelma R. Driving and hindering factors for rural electrification in developing countries: Lessons from Bangladesh. *Energy Policy* 2013; 61: 840-851.

II Rahman MM, Paatero JV. A methodological approach for assessing potential of sustainable agricultural residues for electricity generation: South Asian perspective. *Biomass and Bioenergy* 2012; 47:153-163.

III Rahman MM, Hasan MM, Paatero JV, Lahdelma R. Hybrid application of biogas and solar resources to fulfill household energy needs: A potentially viable option in rural areas of developing countries. *Renewable Energy* 2014; 68:35-45.

IV Rahman MM, Paatero JV, Lahdelma R. Evaluation of choices for sustainable rural electrification in developing countries: a multicriteria approach. *Energy Policy* 2013; 59: 589-599.

V Rahman MM, Paatero JV. Integration of centralized photovoltaic (PV) system into a rural electric feeder at Laxmipur in Bangladesh. *The 3rd International Renewable Energy Congress.* Hammamet, Tunisia 20-22 December 2011. Tunis 2011, Centre de Publication Universitaire, 373-379.

Author's contribution in the published articles [I-V]

The thesis author is the principal contributor of all five original publications [I-V]. Dr. Jukka Paatero provided huge comments and corrections to all the five publications. Professor Risto Lahdelma provided plenty of suggestions and corrections to papers [I], [III] and [IV]. In publication [III], Mohammad Mahmodul Hassan conducted biogas plants survey and provided survey data.

Other publications by the author not included in the thesis

1. **Rahman** MM, Mostafiz SB, Paatero JV, Lahdelma R. Extension of energy crops on surplus agricultural lands: A potentially viable option in developing countries while fossil fuel reserves are diminishing. *Renewable and Sustainable Energy Reviews* 2014; 108-119.
2. Elojärvi M, Poudyal A, **Rahman** MM**,** and Paatero JV. Review on rural energy policy: Nepal, Ghana, Bangladesh, and Zambia. *4th International Conference on Sustainable Energy and Environment (SEE 2011)*. 23-25 November 2011, Bangkok, Thailand.
3. **Rahman** MM, Paatero JV. Electricity generation from agricultural residues in five South Asian countries: Prospects and potential**.** *4th International Conference on Sustainable Energy and Environment (SEE 2011)*. 23-25 November 2011, Bangkok, Thailand.
4. Alanne K, Saari K, Kuosa M, **Rahman** MM, Martin A, Pohjola H. Micro-Cogeneration and Desalination Using Rotary Steam Engine (RSE) Technology, *Microgen'II, the 2nd International Conference on Microgeneration and Related Technologies,* University of Strathclyde, Glasgow, April 4-6 2011.

Notation and abbreviations

Notation

a	annuity coefficient of capital cost	[-]
B_{bat}	lifetime throughput of battery	[kWh]
c_{boiler}	boiler marginal cost	[US$/kWh]
$C_{cap,\mathrm{PV}}$	capital cost of PV system	[US$]
$C_{cap,t}$	present value of capital cost for year t	[US$]
C_{ener}	annual income from energy selling	[US$/y]
C^{FC}	fuel cost	[US$/MJ]
$C_{\mathrm{fuel},t}$	present value of fuel cost for year t	[US$]
$C_{in,\mathrm{t}}$	cash inflow for year t	[US$]
$C_{out,\mathrm{t}}$	cash outflow for year t	[US$]
$C_{O\&M,t}$	present value of O&M costs for year t	[US$]
C_{per}	periodic cost incurred by the system	[US$/y]
$C_{\mathrm{replace},t}$	present value of replacement cost for year t	[US$]
C_T	unit capital cost of distribution transformer	[US$/kVA]
D	annual debt payment	[US$/y]
E_{all}^{hc}	annual thermal potential of all crop types	[GJ/y]
E_{all}^{hl}	annual thermal potential for all livestock species	[GJ/y]
E_e	annual electricity generation	[kWh/y]
E_i^{hcad}	annual thermal potential of residue of crop type i	[GJ/y]
E_j^h	annual thermal potential of livestock type j	[GJ/y]
E_{served}	electric load served	[kWh/y]
E_{tot}^{hcl}	total annual thermal potential of crops and livestock	[GJ/y]
f_{bat}	number of charge cycles of the battery	[-]
f_d	debt ratio	[-]
H_{served}	annual thermal load served	[kWh/y]

I	capital cost	[US$]
L_{ap}	daily appliances load	[kWh/d]
L_c	daily cooking load	[kWh/d]
L_L	daily lighting load	[kWh/d]
M_j	annual manure production of livestock species j	[t/y]
N_j	head count of livestock type j	[thousands]
P_{bat}	battery lifecycle cost per kWh	[US$/kWh]
P_e	power plant capacity	[kW]
P_{PL}	anticipated load of the village	[kW]
p^{cf}	plant capacity factor	[%]
p_f	power factor of transformer	[%]
P_{fw}	price of fuelwood	[US$/kg]
P_k	price of kerosene	[US$/kg]
$P_{O\&M,bat}$	battery lifetime maintenance cost per kWh	[US$/kWh]
P_u	price of urea	[US$/kg]
Q_{fw}	heating value of fuelwood	[MJ/kg]
Q_k	heating value of kerosene	[MJ/kg]
Q_{mc}	heating value of biogas	[MJ/m^3]
r	real interest rate	[%]
r_e	energy cost escalation rate	[%]
R_i	gross residue amount for crop type i	[t/y]
R_i^{th}	annual theoretical available residue for crop type i	[t/y]
r_j^{bg}	biogas generation rate from volatile solid of livestock type j	[m^3/kg]
r_j^{rgr}	residue generation rate	[kg/y]
$R_{\text{salvage},t}$	present value of salvage price for year t	[US$]
s	fraction of generated power consumed by auxiliaries	[-]
S_{bat}	nominal capacity of battery	[kWh]

S_{PV}	capacity of PV system	[W]
t_{bat}	battery life	[y]
x_d	length of electrical distribution line	[km]
Y_i	annual crop yield of crop type i	[t/y]
β	fraction of capital cost for annual O&M	[-]
ϕ^{HR}	heat rate	[MJ/kWh]
η_{dod}	acceptable depth of discharge	[%]
η_e	conversion efficiency from biogas to electricity	[%]
η_{fw}	efficiency of fuelwood for combustion by cook-stove	[%]
η_i^m	biogas generation rate from volatile solid of crop type i	[m³/kg]
η_i^{rdf}	residue dryness factor for crop type i	[-]
η_i^{rrf}	residue recovery factor for crop type i	[-]
η_i^{ryr}	residue to yield ratio for crop type i	[-]
η_i^{vs}	ratio of volatile solid to dry matter for crop type i	[-]
η_j^{rcf}	residue collection factor of livestock type j	[-]
η_j^{dm}	fraction of dry matter of residues of livestock type j	[-]
η_j^{vs}	ratio of volatile solid to dry matter of livestock type j	[-]
η_k	efficiency of kerosene for lighting	[%]
η^{saf}	surplus availability factor	[-]
μ^{FC}	plant capacity factor	[%]
ψ^{LF}	load factor	[%]

Abbreviations and acronyms

BREP	Bangladesh Rural Electrification Program
CRF	Capital Recovery Factor
DGE	Digester Gas Engine
Dgen	Diesel generator
ESMAP	Energy Sector Management Assistance Program

HHC1	Household Category 1
IPP	Independent Power Producer
IRR	Internal Rate of Return
LCOE	Levelized Cost of Energy
MCDA	Multicriteria Decision Analysis
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
REP	Rural Electrification Program
SCR	Saving Cost Ratio
SMAA	Stochastic Multicriteria Acceptability Analysis
TAC	Total Annualized Cost
TAS	Total Annual Saving

1. Introduction

1.1 Background and motivation

Access to electricity is a necessary precondition in bringing about social and economic development in the underprivileged rural areas of developing countries[1] [1-4] . Electricity allows for the enhancement of productivity and thus brings prosperity and eradicates the worst effect of poverty in rural areas. By considering its great importance, governments and the international community have long been emphasizing expansion of electricity service to the population of developing countries [6,7]. Despite the continuous efforts, the rural electrification progress in many developing countries is distressfully slow [8,9], and still today 1.3 billion people in the developing world do not have access to electricity, and 85% of them live in the rural areas.

Rural electrification is characterized by many challenging features, such as small and disperse nature of loads, low level of consumption, rough terrain, and lack of infrastructure. These features make the rural electrification process a much more complex task than electrification of urban areas [10-12]. Rural electrification programs require special form of policy and institutional frameworks for operating and maintaining this complex task. Also, power generation from fossil fuel sources inflicts a burden on the economy, and many developing countries suffer power shortages in serving their rural people. The shortage in power generation capacity is one of the key reasons for the resulting underachievement and sluggishness of the rural electrification task [13,14].

Rural areas are often economically unfeasible for grid extension. Moreover, in many cases, after achieving a certain level of electrification, the remaining areas are unlikely to be viable for grid expansion [12]. Off-grid renewable energy options, on the other hand, have evolved as promising through the maturation of small-scale technologies such as solar photovoltaic (PV) systems, biogas digesters, small wind generators and micro hydropower, etc. Though the renewable energy technologies face many obstacles, their deployment not only accelerates the

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[1] There is no established definition for developed and developing countries in United Nations system. However, United Nations Statistics Division (UNSD) broadly categorized geographic areas into developed and developing countries or regions. According to UNSD and common practices, countries except Japan in Asia, Canada and the USA in northern America, Australia and New Zealand in Oceania, and Europe are considered as developing countries or regions [5].

rural electrification process but also relieves a significant burden from the economy of the respective county [11,15]. Many developing countries are endowed with an abundant amount of biomass resources and long hours of daily sunshine [16]. In contrast, in many cases, renewable-based off-grid rural electrification projects have failed due to lack of attention to sustainability issues beyond the financial and technical objectives [17]. Renewable resource-based off-grid rural electrification programs need to involve social, environmental and policy criteria in addition to economic and technical objectives in its planning and decision-making process [18].

Bangladesh, which has been focused on as the case country to provide data for illustrating applied methods and models, possesses similar attributes as many other developing countries [19]. This country has a huge lack of access to electricity for its rural population and it is endowed with an abundant amount of renewable resources.

To ensure electricity in rural areas of developing countries, international organizations, research institutions, and individual researchers have conducted numerous research and case studies to determine the issues influencing the performance of the rural electrification tasks [3,20-22]. These studies have emphasized that rural electrification is a socio-culturally integrated process where the performance of different programs vary with a number of factors [6,23-27]. Research dealing with rural electrification tasks lacks an emphasis on its distinctive features and potential merits from renewable resources and integration of sustainability issues in the decision-making process. To accomplish successful rural electrification for these billion of people, it is essential to employ strategic approaches to overcome the distinct rural electrification challenges, utilize advantages of endowing renewable resources, and integrate sustainability issues in the decision making process.

1.2 Objectives and research questions

Despite the complex nature of rural electrification task, some developing countries (e.g., Thailand, Tunisia, and Costa Rica) have been more successful in providing electricity to their rural population than other developing countries [6]. Evidences show that rural electrification programs can be successful in developing countries if appropriate policies are enacted. To lay effective and successful policies, it is necessary to determine the driving and hindering factors, which influence the performances of rural electrification programs. Despite having advantages of endowing renewable resources, electrification through renewable technologies in rural areas is quite low. Strategic approaches are required to enhance the dissemination of renewable energy technologies. With this background, the overall objective of this thesis is to explore the distinctive features of rural electrification task and present solution frameworks for sustainable and accelerated rural electrification for 1.1 billion people.

To accomplish the overall objective, the thesis is divided into five research questions, whose answers are sought through five appended published articles. Grid-based electrification is the preferred option to accomplish rural electrification, therefore, at the beginning, the research question 1 has pursued to determine the policy elements which influence the performance of on-grid rural electrification program. This research question also sought to formulate the policy elements, which guide the rural electrification program into success with diverse set of program designs. Rural areas are normally located far from the central grid, and very often grid expansion is not a cost effective solution compared with the renewable-based off-grid solutions [2,28]. Research questions 2, 3 and 5 have been meant to determine how potentially renewable resources serve rural electrification and to find suitable approaches to utilize these resources. Research question 4 has been meant to determine how to choose alternatives based on sustainability criteria. The following table denotes the research questions (RQs) and indicates which published article contributed to answering which research question.

Table 1. Research question (RQ) and corresponding article that addresses the question.

Research questions	Addressed by
RQ1. What are the driving and hindering factors and essential policy elements for a grid-based rural electrification program?	Publication I
RQ2. How potentially agricultural residues can be utilized to generate electricity in rural households of selected South Asian countries without conflicting with other applications?	Publication II
RQ3. How potentially hybrid biogas and solar PV systems can serve both clean-cooking and electricity loads in rural households, and what are their monetary benefits and implications over conventional fuels?	Publication III
RQ4. How to choose among technology options, considering all sustainability dimensions in rural electrification program?	Publication IV
RQ5. Can power generation through integration of PV system into rural grid be competitive over fossil fuel based private independent power?	Publication V

1.3 Scope of research and applied approach

There are generally two technical options for bringing electricity to rural areas. The first option is the extension and intensification of the central grid while the second option is off-grid technologies (in the form of standalone or mini-grid). Grid extension is the most common mode of electrification and has been the preferred option by policy makers and clients due to its well-known advantages (including reliability, unrestricted capacity, economies of scales, and independence from weather conditions) [29-32]. This thesis primarily seeks rural electrification solutions through grid expansion. As the grid expansion is not a feasible option in many cases, the renewable resource-based off-grid option then come as an alternative option. Among different renewable resources, solar and biomass (particularly agricultural residues) are very common in developing countries, including Bangladesh. Therefore, these two resources mainly have been emphasized in this thesis as the main off-grid rural electrification options. Overall, this thesis focuses on rural electrification aspects of the developing countries. However, special focus is given to South Asian regions, particularly Bangladesh, to illustrate the methodologies and to answer the research questions.

1.4 Contributions of the thesis to add new knowledge

This dissertation adds new knowledge to the rural electrification literature in several ways. Firstly, this dissertation evaluates a rural electrification case to determine the major driving and hindering factors behind the performance of the rural electrification program from the developing country perspective (Publication I). As a result, it accumulates new insights on the policy ingredients that are essential for a successful rural electrification program. Secondly, this thesis proposes a methodology of systematically assessing the energy potential of agricultural residues converting through anaerobic digestion process and shows that rural households have significant potential to generate electricity from residues in competitive ways (Publication II). The determination of energy potential via anaerobic digestion and by-correlating data directly with annual crop and livestock yields brings novelty to this work. Thirdly, this thesis also shows that hybrid biogas and solar resources can potentially serve both thermal (clean-cooking) and electricity loads of rural households, incurring more savings than costs (Publication III). The assessment of hybrid biogas and solar resources and their evaluation techniques bring new information to the household-level energy evaluation literature. Fourthly, despite multicriteria decision choices being an integral part of the long-term sustainability of rural electrification projects, the stochastic multicriteria approach has not been adequately incorporated in rural electrification projects. This work incorporated and demonstrated the use of SMAA (Stochastic Multicriteria Acceptability Analysis, a multicriteria decision aiding tool) in the rural electrification decision-making process, which brings a new dimension to the rural electrification literature (Publication IV). Fifthly, this thesis presents a methodological technique to check the economic viability of PV system integrated into a rural electric feeder (Publication V). The proposed technique and illustration add a new discussion in the rural electrification literature.

2. Concept and definition of rural electrification in developing countries

2.1 Defining the scope of rural electrification

Rural electrification is the process of bringing electrical power to rural and remote areas. Researchers use this concept with diversity of interpretations. Frequently, a rural electrification program refers to the administrative units responsible for electrifying rural or remote areas [33]. Although the term ‘rural electrification’ generally means expansion of the electricity connections through the central grid, rural electrification through grid expansion is not an economically superior option in every rural area [10]. According to another definition, rural electrification is the provision of electricity to rural areas for the use of rural communities, regardless of the generation sources and technologies [34]. The World Bank and other international organizations, however, have applied a broader view in utilizing the term ‘rural electrification’. According to the World Bank, IEA, and ESMAP, rural electrification is the facility of bringing electricity to the rural or remote areas of a country through grid or off-grid or even combined technologies [7,8,12,21,31,35].

2.2 Sustainable rural electrification

According to sustainable development definition and millennium statements of World Energy Council (WEC), sustainable rural electrification is the provision of electricity services to the rural people by complying the following objectives: available in terms of continuity of supply and reliability, affordable in terms of price, and acceptable in terms of social and environmental objectives [36,37,38]. In other words, sustainable rural electrification means providing electricity services to the rural population reliably and cost efficiently, and complying with social and environmental needs. Despite electricity generation from fossil fuel sources causes a major portion of global-level greenhouse gas emissions, grid-based rural electrification in the developing countries does not cause such strong emissions. Moreover, grid-based rural electrification is considered as the preferable option for its wide ranging acceptability and advantages [31]. On the other hand, for many rural areas, renewable-based off-grid options can be the adaptable and flexible rural electrification option if their selections are based on social, environmental, and economic objectives. This thesis considers ‘sustainable rural electrification’ as the provision of electricity services to rural areas, either through efficient, equitable and effective grid expansion or through viable renewable energy technologies.

2.3 Technology options for rural electrification

Rural electrification is placed high on the socio-political development agenda in almost every developing country. But besides the policy issues, the other major problem is the selection of technologies. The choice of technology for rural electrification mostly depends on resource availability, distance from the central grid, load types, geographic features of the targeted areas, characteristics of local community, existing infrastructure, and availability and maturity of any chosen technology [23]. The selection of technology is also influenced by the policy and institutional framework and the socioeconomics of the rural areas [18]. The potential technologies for rural electrification is a group of a large number of options and each technology varies in many aspects, such as generation techniques, per-unit energy costs (*LCOE*), initial capital cost, reliability of services, availability in local markets, and the employment of local skills and manpower. The most common technologies used in rural electrification programs are extension of national or regional grid, off-grid renewable technologies (which include photovoltaic, wind turbine, hydropower, bioenergy), and diesel generators or hybrid systems.

3. Methodological frameworks

This section presents a brief overview of the methodological frameworks, which were applied in answering the five research questions. It also provides theoretical support to validating and identifying the implications to apply the methodologies and data. This section is divided into five sub-sections, where each sub-section deals with applied methodology against each research question.

3.1 Rural electrification through grid extension (Publication I)

Extension of the grid is the primary option for providing electricity access to rural areas. A grid-based electricity supply is the first preference by the clients, policy makers, and other stakeholders, because it has numerous advantages, such as reliability, unrestricted capacity, and weather independence. Globally, only a few developing countries are successful in providing electricity to rural population through grid extension, whereas many countries still have remained unsuccessful. This sub-section analyzed the challenging features of rural electrification program to bring understanding on the performance factors of grid-based rural electrification program. The institutional features of Bangladesh rural electrification program were also presented to validate its characteristic factors behind the performance.

3.1.1 Challenging features of extending grid-based rural electrification

(Presented in generic form for developing countries)

Despite being preferred over off-grid options, rural electrification through grid extension poses many distinctive challenges.

Rural areas have many characteristics that make their electrification more challenging compared to urban areas [6,28]. In rural areas, agricultural activities are dominant, the ratio of labor to capital is high, and income is on average quite low. Due to disperse nature of households, number of connections per km of power line is quite low. Power consumption per connection is also low due to lack of productive energy uses (lack of industries). These cause power demand per km of distribution line very low. Hence, the costs per connection and per supplied kWh are significantly higher. Due to poor communications and bad terrain, operation and maintenance are more problematic and costly, and the quality of power supply is often quite low [10].

Rural people in developing countries are remained in the bottom section of the pyramid and usually cannot afford the full cost of the high initial investment. In addition to community equity and credit from donor agencies and the government, rural electrification usually requires some form of subsidy from the government to cope with the high capital cost [39]. The subsidy, if not administered properly, causes problems. For instance, it can create opportunities for politicians to intervene, because politicians feel they have the right to participate in decision making while the financing are based on subsidy, which destroy impartial management practices. The subsidy often makes the program prone to unfair practices such as restoring connections that have been cut off due to lack of payment, stealing of power and other illegal activities, and bypassing the criteria for the selection of loads. Also, poorly designed subsidies deviate the electricity distribution company from customer service to money maximization. This causes the rural electrification program to alienate the customer, and compromise the quality of its service [6].

The right-of-way[2] access also causes problems in rural areas where the overhead lines criss-cross croplands, houses, or a land reserved for future households. The local community may also seek compensation against the right-of-ways, which is usually not budgeted in rural electrification schemes. The load factor in rural areas is quite low, and the demand is generally concentrated in the peak evening times. This requires a high peak capacity for the conductors and other equipment, which leads to higher costs. Another challenge in rural electrification has to do with the grid expansion versus the off-grid dilemma. Many politicians have a strong preference for extending the national grid irrespective of viability [31].

Besides the above challenges, counties with low-lying and hilly lands also face a few exceptional challenges. Bangladesh, for example, has almost 800 rivers and tributaries that crisscross and pass through the country. Most of the country’s rivers are characterized by massive land erosion and changing water courses every year. This means that many rural areas face the challenge of removing the grid lines and expanding the grid. Massive river erosion also causes new areas to form, which are called “chars” (islands), through silt deposition within the water course. Although thousands of people may live on the newly formed ‘chars’, extending the grid lines to the chars is both unfeasible and impractical.

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[2] The idea of ‘right-of-way’ is the right to build the distribution infrastructure across someone’s property without expecting any legal challenge in the future.

3.1.2 Determination of the factors contributing to performance

The Bangladesh rural electrification program (BREP) received a very distinctive status in developing countries with respect to its highly representative features. The program pioneered in successfully tackling the typical adverse socio-economic and turbulent political conditions in the developing country situations. Rural electrification programs involved multiple aspects, such as technology and institutional and financing policy issues, and there appears to be no clear methodological framework to deal with the aspects together. Therefore, this thesis used exploratory research approach to evaluate the performances and determine the driving and hindering factors behind the performance of BREP. At this point, I give a brief institutional overview of BREP to elucidate performance features that are connected with the institutional framework. Bangladesh adopted the rural electric cooperative (REC) concept in its rural electrification program. According to this concept, a central statutory agency called the Rural Electrification Board (REB) was formed, which was given the responsibility of organizing the rural electric cooperatives (Palli Bidyut Samity, PBS). The cooperative is a consumer-owned autonomous organization responsible for delivering electricity to designated rural areas. The REC (PBS) constructs, operates, and manages its own electricity distribution system. REB supervises the financial and administrative activities of the cooperatives through managers (Figure 1) [24]. Consumers of the cooperative elect a board of directors, which formulates the cooperative's policy and implements the policies through managers. The cooperatives obtain funding from government and donor agencies and REB acts as a conduit to channel funding to the cooperatives.

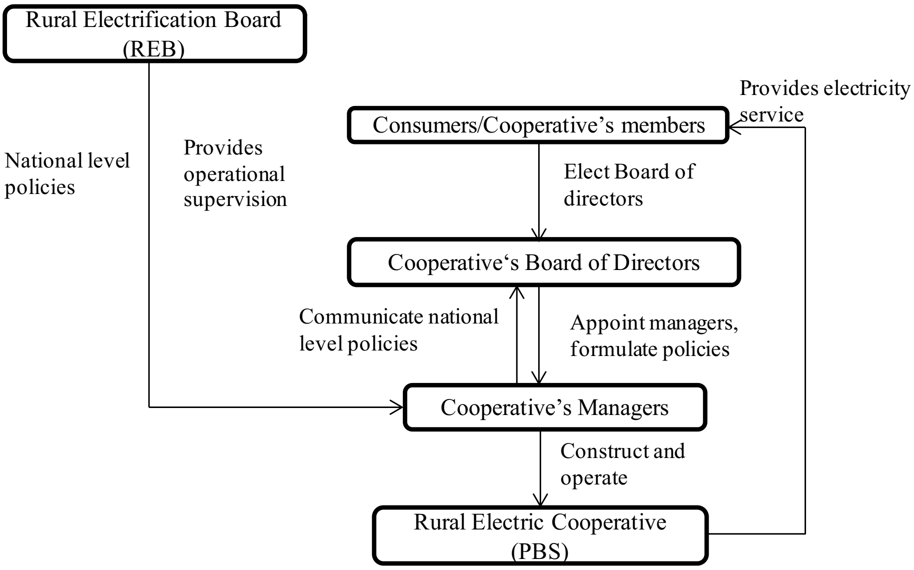

Figure 1. Institutional framework of Bangladesh Rural Electrification Program.

3.2 Methodology for assessing the potential of sustainable agricultural residues in five South Asian countries (Publication II)

Biomass is the source of fuel for subsistence in most of the South Asian developing countries. Biomass products like firewood, charcoal, manure, and crop residues provide the main source of household energy for around one billion people in South Asian countries [40,41]. Among renewables, bioenergy is the most promising, as its mobilization can stimulate employment generation, combat desertification, and prompt gender equity activities [42]. The agricultural residues, which include crop residues and animal manure, provide a major part (e.g., 80% to 90%) of the cooking fuels for rural households [43]. Agricultural residues cover a wide spectrum of leftovers derived from crops and livestock such as rice straw, corn cobs, sugarcane bagasse, cattle manure, poultry dropping, etc. The most significant classifications of these residues are- crop residues and animal manure. Although the agricultural residues are widely used, their conversion efficiency is very low and a significant portion is wasted and poorly managed. Despite a huge amount of residues being produced every year in the rural areas, their application through cleaner conversion is limited. This thesis determines the electricity generating potential from this resource in meeting rural households' demands by complying with environmental, economic and societal constraints.

3.2.1 Assessing the potential of crop residues

The term ‘crop residue’ is used to describe all the organic materials that are produced as by-products from harvesting and the processing of agricultural crops. These crop residues can be further categorized into- field residues and process residues. Crop residues that are generally in the field at the time of harvesting are defined as field residues (e.g., rice straw, wheat straw), whereas those co-produced during processing of the crops are called process residues (e.g., rice husk, bagasse) [44].

The residues usually lay in scattered places in the fields and process sites, and they possess diverse characteristics. The availability of residues depends on many different issues and constraints. Moreover, all residues are not readily applicable for modern energy uses. The assessment of the sustainable residues is associated with the steps presented in Figure 2.

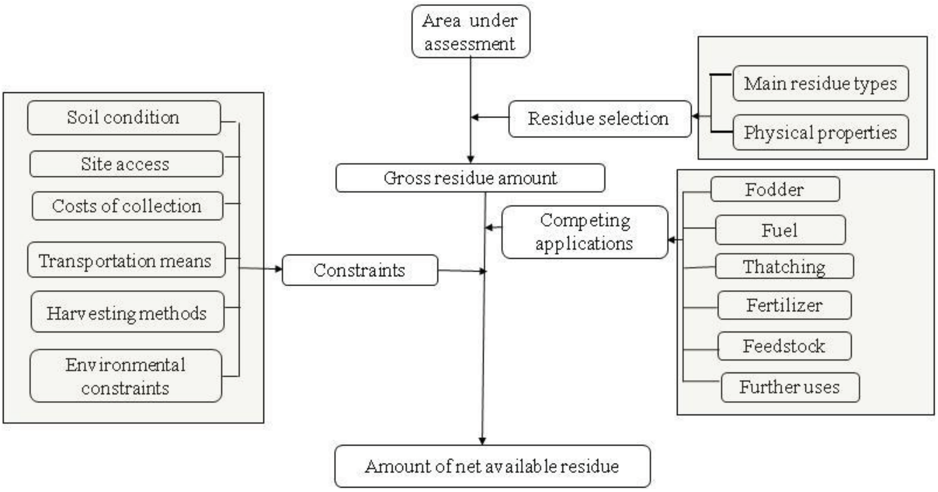

Figure 2. Residue assessment steps.

Gross residue amount of any crop species: The gross residue amount R_i (t/y) generated annually by the crop type i can be obtained in Eq. (1)

$$R_i = Y_i \cdot \eta_i^{ryr} \tag{1}$$

where Y_i (t/y) is the annual crop yield and η_i^{ryr} is the residue-to-yield ratio of crop type i. The residue-to-yield ratio indicates how much residue (mass) is generated per unit of crop products of any crop type. The annual average yields of main crop types can be determined from the regional, national or international statistics. The values of η_i^{ryr} vary with several factors, such as crop varieties, harvesting seasons, harvesting practices, fertilizer use, etc. [45].

The amount of residues obtained from Eq. (1) is not entirely available; rather, there are several active uses for this resource, such as fodder, fuel, and thatching [3]. Several estimations of the surplus availability factors η^{saf} have been presented in the literature [41,44,46,47]. Also several constraints limit the accessibility of the residues, such as soil condition, transportation means, landscape, harvesting methods, and adverse effects on future yields. Considering all these factors, the *amount of net available residues* (field or process) R_i^{th} (t/y) for crop type i can be obtained in Eq. (2).

$$R_i^{th} = R_i \cdot \eta_i^{rrf} \cdot \eta_i^{saf} \tag{2}$$

where η_i^{rrf} is the residue recovery factor (kg/kg of residue) and η_i^{saf} is the surplus availability factor (kg/kg of residue) for field or process-based residues for crop type i . Each crop species eventually gives the residue amount by summing up the amounts for both residue types (i.e., field and process).

Despite the biomass being renewable in nature, it faces a number of drawbacks when its utilization involves a combustion process. In contrast, the anaerobic digestion (AD) process has been recognized as the lowest cost and environmentally friendly technology to convert biomass into biogas in a rural context [48]. Therefore, it will be worthwhile to ascertain the energy potential of residues through AD to completely utilize the residues and minimize the adverse effects on the environment. The annual thermal potential E_i^{hcad} (GJ/y) of residues of crop type i through AD process can be determined in Eq. (3)

$$E_i^{hcad} = R_i^{th} \cdot \eta_i^{rdf} \cdot \eta_i^{vs} \cdot \eta_i^{m} \cdot Q_{mc} \tag{3}$$

Here η_i^{rdf} is the residue dryness factor (kg/kg of residue), η_i^{vs} is the ratio of volatile solid (VS) to dry matter (DM), η_i^{m} is the biogas generation rate (m^3/kg of VS) of crop species i, and Q_{mc} (MJ/m^3) is the heating value of biogas. The total annual thermal potential of all crops E_{all}^{hc} (GJ/y) can be calculated by summing up the annual thermal energy potentials of the residues of all crop types as given in Eq. (4) below:

$$E_{all}^{hc} = \sum_{i=1}^{I} E_i^{hcad} \tag{4}$$

3.2.2 Assessing the potential of animal manure

Anaerobic decomposition of animal manure produces methane gas (CH_4), carbon dioxide (CO_2), and stabilized organic materials. The potential for the generation of electricity from livestock manure can be calculated considering its transformation into biogas via anaerobic digestion. Livestock such as cattle, buffalo, sheep, goat, and poultry are common in South Asian rural areas [49]. The dung production from animals depends on many factors, such as the body weight of the animals, the type and quality of the feeds, and physiological states [50]. The literature suggests the average residue generation rates for varieties of livestock in different regions of the world [41,50,51]. The annual manure production M_j (t/y) of livestock species j can be obtained in Eq. (5)

$$M_j = N_j \cdot r_j^{rgr} \tag{5}$$

where N_j (in thousands) is the head count of livestock type j and r_j^{rgr} (kg/y) is the residue generation rate. Accessibility of the dung is an important factor, particularly where livestock are range-fed, and consequently the dung is not easily accessible. However, the dung from cattle can be collected from the droppings at the cattle sheds, which are generally stationed in rural areas [52]. The annual thermal potential E_j^h (GJ/y) of livestock type j can thus be obtained by Eq. (6):

$$E_j^h = M_j \cdot \eta_j^{rcf} \cdot \eta_j^{dm} \cdot \eta_j^{vs} \cdot r_j^{bg} \cdot Q_{hvl} \tag{6}$$

where η_j^{rcf} is the residue collection factor (kg/kg of residue), η_j^{dm} is the fraction of dry matter of residues (kg/kg of residue), η_j^{vs} is the ratio of volatile solid to dry matter, r_j^{bg} is the biogas generation rate (m^3/kg of VS) of livestock species j, and Q_{hvl} (MJ/m^3) is the lower heating value of biogas. As a result, the total thermal potential of animal manure for all major species E_{all}^{hl} (GJ/y) can be calculated as Eq. (7)

$$E_{all}^{hl} = \sum_{j=1}^{J} E_j^h \tag{7}$$

The thermal outputs from the co-digestion of all of the residue species are not available in the literature. However, it is obvious from the literature that co-digestion between crop and livestock residues produces more biogas than their separate digestion if optimum digester conditions (e.g., temperature, pH, organic loading rate) are maintained [53]. This thesis assumed that the total thermal potential of crop and livestock residues E_{tot}^{hcl} (GJ/y) is equal to the sum of their individual yield and can be determined by Eq. (8) as follows:

$$\mathrm{E}_{\mathrm{tot}}^{\mathrm{hcl}} = E_{all}^{hc} + E_{all}^{hl} \tag{8}$$

3.2.3 Economic evaluation of the residues for electricity generation

The levelized cost of energy production (*LCOE*) is one of the popular tools used to evaluate the viability of an energy system [54, 55]. Based on the heating value of the biogases from the possible residues, the levelized cost of energy production, *LCOE* (US$/kWh), can be determined by the Eqs. (9-11):

$$P_e = \frac{E_{tot}^{hcl}}{3.6 \times 8.76} \cdot \eta_e \tag{9}$$

$$E_e = P_e \times 8760 \times p^{cf} \tag{10}$$

$$LCOE \cdot E_e = a \cdot I + C_{O\&M} - R + C_f \tag{11}$$

where E_{tot}^{hcl} (GJ/y) is the total annual thermal potential of crop and livestock residues, P_e (kW) is the plant capacity, and η_e is the conversion efficiency from biogas to electricity, which is around 26% for a gas engine [50]. Also, E_e is the annual electricity generation (kWh/y), p^{cf} is the plant capacity factor, a is the annuity coefficient of the capital cost, I (US$) is the capital cost, $C_{O\&M}$ (US$/y) is the annual operation and maintenance cost, R (US$/y) is the revenue from by-products, and C_f (US$/y) is the fuel (residue) cost.

Besides *LCOE*, the Net Present Value (*NPV*) and Internal Rate of Return (*IRR*) are the financial indicators commonly used for to evaluate an energy project and to create insight into the project's profitability [55,56]. The *NPV* (US$) and *IRR* (%) can be obtained using Eqs. (12-13)

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \tag{12}$$

$$0 = \sum_{t=0}^{T} \frac{CF_t}{(1+IRR)^t} \tag{13}$$

where CF_t (US$) is the net cash flow of the investment in year t, which can be calculated as $CF_t = a \cdot I + C_{O\&M,\mathrm{t}} - R_t + C_{f,\mathrm{t}}$ and T (y) is the plant life, and r (%) is the real interest rate. Despite a few limitations, these two indicators are widely used for a project's financial analysis [54].

3.2.4 Applied data for the assessment of residue potentials

To establish the main characteristic values of the major crops and livestock, a selection of literary sources were used [41,45,47,50,57,58,59,60]. The crop species which were considered in this study are rice, wheat, maize, jute, sugarcane, cotton, pulses, coconut, millet, and vegetables, while the livestock are cattle, buffalo, goats, sheep, horses, and chickens.

3.3 An approach for evaluating hybrid applications of biogas and solar resources (Publication III)

Electricity and thermal energy for cooking are the two energy forms essential in the rural areas. Renewable resources- biomass (resource for biogas) and solar are abundantly available in the rural areas of many developing countries and pose potential to serve both thermal (cooking) and electricity demands. Biogas and solar resources separately, however, are not feasible to meet these two forms of energy demand. This section presents methodological framework for examining the techno-economic performance of hybrid applications of these two renewable resources

3.3.1 Concerns associated with current fuel applications

The rural household usually uses conventional cookstove and wet (i.e. with moisture content $\geq 15\%$) solid biomass as fuel for cooking purposes. The low efficiency stove with wet solid biomass produces a high level of smoke that is hazardous for human health. Lighting using a paraffin candle and a kerosene lantern emits smoke, and they produce poor lighting intensity per unit of consumed wattage. Other basic energy applications such as the provision of entertaining/leisure, communication, and space cooling (fans) require electricity. Thus, there is a crucial need to provide clean gaseous fuel for cooking and electricity for other basic applications in rural households. Many developing countries produce plenty of bio-waste from livestock every day and have many hours of daily sunshine [41,61].

3.3.2 Framework for alternative fuel applications

The main energy use in rural households is for cooking and lighting purposes. The other basic energy requirements beyond cooking and lighting are space cooling, home appliances for leisure, and cell-phone charging. Because of geography and climate conditions, space and water heating needs in rural households are very small in many developing countries [62]. In Bangladesh, households use a wide range of energy sources for cooking, such as fuelwood, agricultural residues, kerosene, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and biogas. The uses of other fuels, such as plant oils, biomass briquettes, charcoal, and electricity, are very small or negligible. The lighting services are provided by some form of external sources such as kerosene, paraffin candle, etc. The other energy services such as leisure/entertainment and cell-phone battery charging are provided by car-battery or dry-cell battery [19].

In Bangladesh, three-stone burners are used for cooking by biomass fuels, and kerosene stoves are used for cooking by kerosene and LPG/LNG fuels. Lighting services in the rural households are provided by paraffin candles, hurricane lantern, or wicks lamps. The common appliances for leisure/entertainment and communication are radio, cassette player, TV, and mobile phone. Beyond theses appliances, some other home-appliances (such as refrigerator, hair-dryer, rice-cooker, and flat-iron) are also used in a few households. Households' current energy applications, fuel sources, devices/appliances, and possible alternative forms are presented in Figure 3. Two forms of renewable fuels (e.g., biogas and solar) have been focused on in this study as the alternative fuels to meet household energy needs [19,63,64,65].

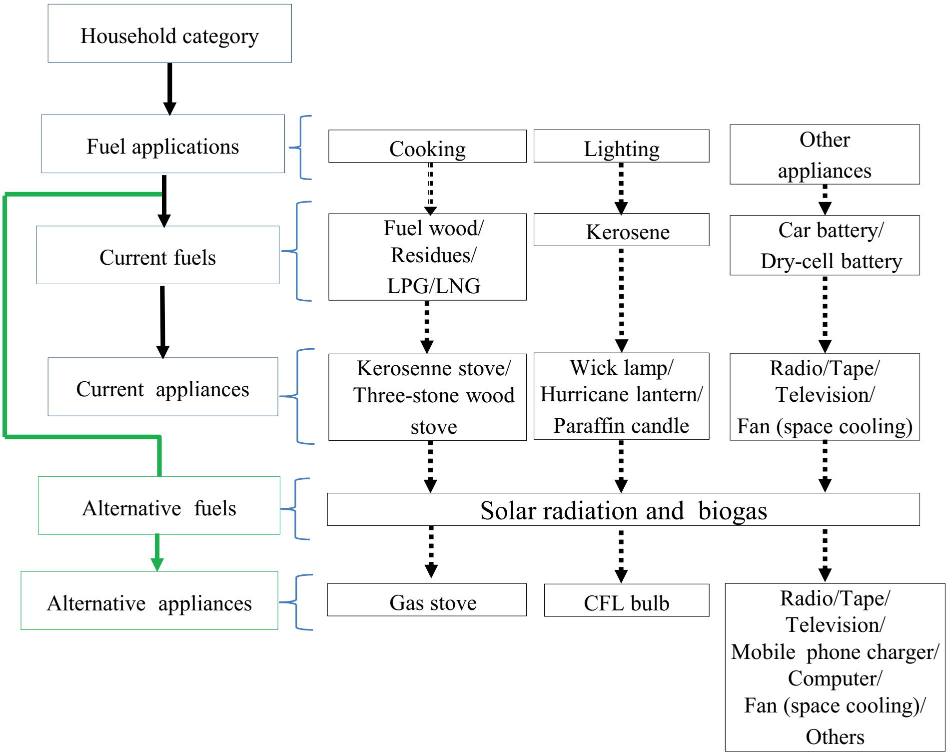

Figure 3. Framework for current and alternative fuels and appliances in rural households.

3.3.3 Biogas generation

One kilogram of fresh cattle dung has the potential to generate about 0.04 m^3 of biogas. In other words, 25 kg of cattle dung is required for producing 1 m^3 of biogas [66]. One cattle on average gives 10 kg of fresh dung per day. Biogas plants (sometimes referred to as anaerobic digesters), which is an assembly of a few containers (tanks) and pipes, convert livestock wastes into biogas. Household-scale biogas plants usually consist of an airtight underground digester tank, a gas holder, two inlet outlet tanks, a mixing device, a few pipes, and gas regulator valves (see Figure 4). The digester tank gets feed in with properly mixed bio-wastes and water. The size (or in other words, the capacity) of biogas plants corresponds to the quantity of biogas (m^3) the plant can produce in 24 hours. Biogas burns with a blue flame without emitting smoke and gives CO_2-neutral combustion [67].

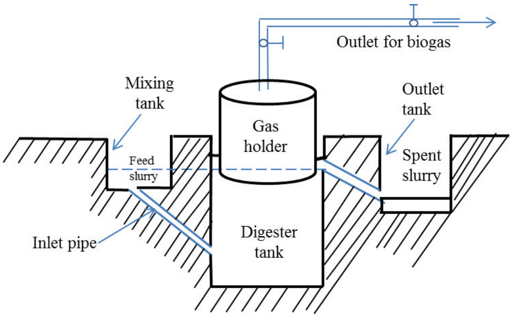

Figure 4. Main components of biogas plants.

3.3.4 Evaluation tool

This thesis first designed hybrid systems from biogas and solar resources that can serve both electricity and thermal demands while complying with technical and resource constraints. Then it performed techno-economic evaluations on the resulting hybrid systems to examine how these two renewable energy resources can potentially serve household energy demands.

This research work considers two energy generation technologies: Digester gas engine (DGE) and solar PV system. Among different approaches, simulation-based optimization is a widely utilized approach for designing small-scale energy systems and performing economic evaluations on them [31]. Some common optimization tools are HOMER [68], Hybrid2 [69], and HOGA [70]. Renewable-based power systems entail complexity due to the transient nature of power outputs and variation in availability of renewable resources. This thesis applied the HOMER computer tool because it has the unique capability of handling small-scale renewable-based energy systems. HOMER performs hourly time-series simulations and can incorporate the effects from uncertainties of different input variables such as load sizes, fuel price, and resource availability.

The HOMER tool performs three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, it first simulates the performance of a vast number of system configurations based on energy balance calculations for each hour of the year to determine whether these configurations are feasible. The HOMER tool considers the system to be feasible if it can adequately serve the electric and thermal loads and satisfy all technical constraints imposed by the model users. HOMER tool applies dispatch strategies to determine the charging order for storing of energy. The tool follows two separate dispatch strategies: load-following and cycle-charging. Under the load-following strategy, only renewable power

sources charge the battery but non-renewable sources do not charge. Under the cycle-charging strategy, whenever the system produces surplus power (either from renewable or non-renewable sources), the extra power goes to charge the battery [71].
The model estimates the total net present cost (*NPC*), which is the present value of all costs for installing and operating the system minus the present value of all revenue over its lifetime. The total net present cost (*NPC*) and total annualized cost (*TAC*) of the system are calculated as below:

$$NPC = \sum_{t=0}^{T} (C_{cap,t} + C_{O\&M,t} + C_{replace,t} + C_{fuel,t} - R_{salvage,t}) \tag{14}$$

$$TAC = NPC \cdot CRF(r,\mathrm{T}) \tag{15}$$

where T is the lifetime of the project, $C_{cap,t}$ is the present value of capital cost for year t, $C_{O\&M,t}$ is the present value of operation & maintenance cost for year t, $C_{fuel,t}$ is the present value of fuel cost for year t, $C_{replace,t}$ is the present value of the replacement costs for year t and $R_{\mathrm{salvage,t}}$ is the current value of the salvage price for year t, r is real interest rate and *CRF* is capital recovery factor.

In the optimization process, HOMER ranks the system configuration from many different configurations based on the lowest total *NPC*. Though HOMER ranks the system on total *NPC*, it also calculates the *LCOE* (electricity) value for each of the optimized systems. The *LCOE* (electricity) is the average cost of producing per kWh of useful electrical energy and does not include the thermal part and is calculated using the following equation:

$$LCOE(electricity) = \frac{C_{a,tot} - c_{boiler}.H_{served}}{E_{served}} \tag{16}$$

where $C_{a,tot}$ is the total annualized cost of the system (US$/y), c_{boiler} is the boiler marginal cost (US$/kWh), H_{served} is the total thermal load served (kWh/y) , and E_{served} is the total electrical load served (kWh/y).

3.3.5 Input data for the HOMER tool

HOMER simulation requires lots of data sets as input. The following section describes the techniques used for processing the input data.

3.3.5.1 Anticipated loads and other required parameters

HOMER loads consist of three components: primary load, thermal load, and deferrable load. Primary load is the electrical demand that the power system must meet at any specific time. Thermal load is the heat demand that must be served. And deferrable load is the electrical demand that can be served at any time within a certain time span.

I have categorized rural households into three categories based on energy use information from the Grameen Shakti survey report [72], Asaduzzaman et al. [19], Miah et al. [63], and the World Bank [64].

The daily electric and thermal energy demands for the three household categories (HHC) are presented in Tables 2 and 3. All three household categories (i.e. HHC1, HHC2 and HHC3) have been considered to have basic electric appliances operating 2 to 6 hours per day. The gas burner with 60% efficiency has been considered as a cooking device (as Boiler in HOMER) using biogas as fuel. The gas burner operates 4 to 8 hours a day with a final thermal output per burner of 1.6 MJ/h [1,63,65]. The physical and economic parameters, which were used in economic evaluation, are presented in Table 4.

Table 2. Thermal (cooking) energy demand per household for three households categories.

Load type	Appliance	Thermal output per burner (MJ/h)	Household category					
			HHC1		HHC2		HHC3	
			Burner -hour [a]	Daily final heat consumption (kWh/d)	Burner -hour	Daily final heat consumption (kWh/d)	Burner -hour	Daily final heat consumption (kWh/d)
Cooking	Gas burner	1.6 [b]	4	1.776	6	2.664	8	3.552

[a] A burner-hour is the thermal (cooking) load served by one burner in one hour.

[b] A gas burner approximately gives a final thermal output of 1.6 MJ/h.

Source: [65]

Table 3. Electric energy demand per household for three household categories.

	HHC1	HHC2	HHC3
Daily electricity demand per household (kWh/d)	1.71	2.17	2.49

Sources: [19,63,73]

Table 4. Parameters related to biogas digester and cooking fuels.

Parameters	Symbol	Values	Variations
Calorific value of biogas	Q_b	23 MJ/m^3	
Calorific value of fuelwood (15% moisture)	Q_{fw}	16 MJ/kg	
Calorific value of kerosene	Q_k	43 MJ/kg	
Biogas cook-stove efficiency	η_{bg}	60%	
Efficiency of kerosene for lighting	η_k	6%	
Fresh dung required to produce 1 m^3 of biogas	d_w	25 kg	
Nitrogen available in fresh dung	N	2%	
Nitrogen retention factor	h_b	60%	
Price of kerosene	P_k	1.0 US$/kg	
Efficiency of fuelwood for cooking	η_{fw}	15%	
Price of fuelwood	P_{fw}	0.02 US$/kg	0.01-0.07 US$/kg
Price of urea	P_u	0.25 US$/kg	
Price of cattle dung[a]	P_d	0.25 US$/m^3	0.10-0.50 US$/m^3
Lifetime of the project	t_{proj}	20 y	
Real interest rate	-	5%	

[a] Note: The price of cattle dung is expressed in US$/m^3, which directly corresponds to price (in US$) of 25 kg of cattle dung.

Sources: [2,7]

3.3.5.2 Electrical load profile

The HOMER model requires an hourly load profile to enable hourly simulation of the system by making energy balance calculations for each of the 8,760 hours in a year. I have gathered a monthly-averaged daily load profile for rural areas. This load profile is based on the real loads of 8.2 million rural consumers connected to the electric distribution network in Bangladesh [74]. The daily and hourly noise inputs allow adding randomness to the load data, enabling the load profile to be more realistic. I have incorporated randomness by applying daily 15% and hourly 10% noise inputs.

3.3.5.3 Costs of system components

Capital cost for a solar PV system: To obtain the capital cost of PV systems of various sizes, I applied a generalized cost function equation (Eq. 17) [75] .

$$C_{cap,PV} = 60.6 + 6.14 S_{PV} \text{; \{Applicable for: } 20W \le S_{PV} \le 500W \text{ \}} \tag{17}$$

where $C_{cav,PV}$ (US$) is the capital cost of a solar PV system of size S_{PV} (W). The solar PV system package includes a PV module, a battery and other accessories. The breakdown of capital costs for each component is as follows: 60% of the cost for the PV module, 25% for the battery, and the remaining 15% of the cost for the converter.

Operation and maintenance (O&M) costs of a PV system: The solar module requires no significant maintenance during its lifetime of over 20 years [76], but the battery unit needs to be replaced several times [77]. Batteries with various lifetimes and of different types are available in the market. Hence it will be appropriate to obtain the annual operation and maintenance cost of a battery from its lifetime maintenance cost per kWh and lifetime throughput (kWh). I have obtained the operation and maintenance cost of battery $C_{a,O\&M,bat}$ (US$/y) with the help of following equations.

$$C_{a,O\&M,bat} = B_{bat} P_{O\&M,bat} / t_{bat} \tag{18}$$

$$B_{bat} = S_{bat} f_{bat} \eta_{dod} \tag{19}$$

where B_{bat} (kWh) is the lifetime throughput of the battery, $P_{O\&M,bat}$ (US$/kWh) is the battery lifetime maintenance cost per kWh, t_{bat} (y) is the battery life, S_{bat} (kWh) is the nominal capacity of the battery, and f_{bat} is the number of charge-cycles of the battery for acceptable depth of discharge (η_{dod}).

Capital cost of the digester gas engine (DGE) system: The cost function equations for gas engines in the range of 0.6-5 kW and bio-digesters in the range of 1.6 - 77 m^3 are taken from Rahman and Paatero [78], which are based on cost data obtained by reviewing markets prices in Bangladesh.

Operation and maintenance cost of the digester gas engine system: The operation and maintenance cost of the digester gas engine system has been obtained from methodology developed by Rahman and Paatero [78].

3.3.6 Determination of savings in terms of monetary worth

The saving is the hypothetical cost that could be incurred if a household consumed the same energy with conventional fuels (i.e. fuelwood and kerosene). It is the value of the conventional fuels displaced by the new fuels. Total annual savings are computed from Eq. (20), which was developed based on the methodology of Kandpal et al. [79], and Bala and Hossain [80].

$$TAS = \left[\frac{3.6L_c}{Q_{fw}\eta_{fw}} P_{fw} + \frac{3.6L_L}{Q_k\eta_k} P_k + \frac{L_{ap}}{\eta_{bat}\eta_{dod}} P_{bat} + 2.15V_{bg} d_w N h_b p_u \right] 365 \tag{20}$$

where TAS (US$/y) is the total annual saving, L_c (kWh/d) is the daily cooking load, Q_{fw} (MJ/kg) is the calorific value of fuelwood, η_{fw} is the efficiency of fuelwood for combustion by cookstove, P_{fw} (US$/kg) is the price of fuelwood, L_L (kWh/d) is the daily lighting load, Q_k (MJ/kg) is the calorific value of kerosene, η_k is the efficiency of kerosene for lighting, P_k (US$/kg) is the price of kerosene, L_{ap} (kWh/d) is the daily appliances load, η_{bat} is the efficiency of battery, P_{bat} (US$/kWh) is the battery lifecycle cost per kWh until the battery reached the maximum limit of depth-of-discharge (η_{dod}), V_{bg} (m^3/d) is the daily biogas consumption, d_w (kg/m^3) is fresh cattle dung required to produce 1 m^3 of biogas, N is the nitrogen available in fresh dung, h_b is the nitrogen retention factor, and P_u (US$/kg) is the price of urea.

Annual savings-to-cost ratio (SCR): The *SCR* is the ratio of the total annual savings from displacing conventional fuels to the total annualized cost for adopting new fuels. The annual savings are calculated from Eq. (19), and the total annualized costs (TAC) are taken from HOMER results as in Eq. (15). The SCR can be calculated as below.

$$SCR = TAS / TAC \tag{21}$$

3.3.7 Household biogas plants survey

The objectives of this survey were to get the users' appraisals on the acceptability and practical applicability of biogas plants. The survey data are based on a primary data collection survey on households' biogas plants, supplied by Grameen Shakti (a private organization serving renewable energy) [72]. The survey covered 72 households from three districts of Bangladesh (39 from Gazipur, 20 from Joipurhat, and 13 from Naogaon). The households were selected to be representative of the typical features of households who own and operate the biogas plants from Grameen Shakti. The survey used a structured questionnaire with 36 questions in 5 sections.

3.4 Multicriteria approach for evaluation of choices for sustainable rural electrification (Publication IV)

Rural electrification requires effective prioritization and planning to enable economic choices of technology by considering socio-economic and environmental consequences [6,12]. A large number of off-grid rural electrification projects have failed due to little or no attention to long-term sustainability issues beyond technical considerations [17]. Case studies indicate that an off-grid supply acts as a pre-electrification option, with the community continuing to aspire for grid connection. Consequently, many off-grid electrification projects are discontinued due to access to grid lines at a later stage of the off-grid projects [3]. Reddy and Srinivas [18] observed that the choice of technology for rural electrification is influenced by various policy, institutional, and socio-economic factors in the rural areas. Appropriate and multi-factorial (multicriteria) decision choices are, therefore, an integral part of long-term sustainability of rural electrification projects.

3.4.1 Criteria for rural electrification

Tshewang [81] proposed an evaluation method for rural electrification options by considering 18 indicators under technical, regulatory, environmental and social dimensions. Elisabeth [82] argues that rural electrification success is allied with as much as 39 indicators under five dimensions, namely technical, economic, social, environmental and institutional sustainability. Ilskog and Kjellström [83] evaluated a rural electrification case using 31 indicators. Cherni et al. [84] proposed a decision-support system to determine an appropriate set of energy options in terms of five factors. A joint UN publication [85] has recommended 39 indicators. These well-defined indicators are suitable measure of five dimensions of sustainability: technical, economic, social, environmental and institutional sustainability. This thesis has compiled and proposed 24 criteria under five sustainability dimensions (Table 5); these criteria potentially lead to an energy system that can retain better sustainability in terms of all 39 energy indicators.

Table 5. Criteria under five sustainability dimensions.

Sustainability dimensions				
Technical dimension	Economic dimension	Social dimension	Environmental dimension	Policy dimension
Criteria under each sustainability dimension				
(1) Capacity utilization factor, %	(7) Capital cost, US$/W	(13) Public and political acceptance	(17) Lifecycle GHG emissions, kg CO_2/kWh	(19) Land requirement and acquisition
(2) Compatibility with future capacity expansion	(8) Annual operation and maintenance costs (fixed), US$/kW	(14) Scope for local employment	(18) Local environmental impact	(20) Emphasis on use of local resources
(3) Compatibility with existing infrastructure	(9) Lifespan of the system, y	(15) Public awareness and willingness		(21) Opportunity for private participation
(4) Availability of local skills and resources	(10) Learning rate, %	(16) Conflict with other applications		(22) Tax incentives, %
(5) Weather and climate condition dependence	(11) Current market share, %			(23) Degree of local ownership
(6) Annual resource availability duration (h/y)	(12) Dependence on fossil fuel, %			(24) Interference with other utilities

3.4.2 Grid versus off-grid decision

Though it is evident from many case studies that off-grid renewable energy systems can play a vital, cost-effective role in supplying electricity to rural areas, these off-grid options are not mutually exclusive. The national or regional utility companies have often structured their grid-extension plan without excluding villages that might have potential for an off-grid supply in future. Therefore, for the long term sustainability of an off-grid system, it is required to know whether the off-grid system will be exposed to grid extension competition in future. The proposed approach first determines whether the electricity supply provision should be grid expansion or off-grid on the basis of the levelized cost of delivered electricity (apple-to-apple comparison). If the grid expansion is not found to be viable, then the SMAA (Stochastic Multicriteria Acceptability Analysis) tool is used for evaluating different off-grid alternatives considering 24 criteria under five sustainability dimensions.

Checking the viability of a grid expansion can be done by comparing the costs of delivered electricity against the off-grid supply costs [86]. At any location, the cost of delivered electricity from the grid has three components: (a) the cost of generation at the bus-bar of the generation plant, (b) cost of transmission, and (c) cost of distribution to the client's meter.

Cost of generation at the plant bus bar: The levelized cost of energy generation is the preferred tool to compare different power generation technologies of unequal economic life, capital cost, efficiencies (or heat rates), and fuel costs [55]. The levelized cost of electricity generation ($LCOE_g$) can be calculated according to the formulae presented below.

$$LCOE_g = \frac{\sum_{i=1}^{m}\left[CRF_i \cdot I_i + E_i \phi_i^{HR} C_i^{FC} + \beta_i I_i\right]}{\sum_{i=1}^{m} E_i} \tag{22}$$

Here i represents the power generating plant (1, 2, ... , m), m is the total number of power generating plants serving to the central grid, E_i is the annual electricity output at the bus bar (kWh) of plant i which can be obtained as $E_i = P_i \mu_i^{CF}(1-s_i)\times 8760$, s_i is the fraction of generated power consumed by the auxiliaries of plant i, CRF_i is the capital recovery factor for plant i of life t years and can be calculated according to Wang et al. [87] as $CRF_i = \frac{r(1+r)^{t_i}}{(1+r)^{t_i}-1}$, P_i is the rated capacity of the generator unit i in kW, I_i is the capital cost of plant i measured in (US$/kW), ϕ_i^{HR} is the heat rate[3] of the plant measured in

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[3] *Heat rate* is the thermal performance or energy efficiency of a thermal power plant for a specified period of time and measured in MJ/kWh. A power plant has *heat rate* 10 MJ/kWh means that 10 MJ of heat energy which is input into the engine will result in conversion to 1 kWh of electricity.

(MJ/kWh), and C_i^{FC} is the fuel cost (US$/MJ), μ_i^{CF} is the plant capacity factor[4], r is the real interest rate, and β_i is the fraction of the capital cost for annual operation and maintenance of plant i.

Cost of transmission of electricity: The power grid serves to transport electric power from the generators to the low voltage distribution substations. The cost of power transmission is associated with capital costs, operation and maintenance costs, and technical losses and depends on the specific power system configuration. The path travelled by electricity through the transmission network is very difficult to trace in a large national electricity transmission network. ESMAP [2] has summarized the levelized cost of power transmission ($LCOE_t$) for four power generation configurations from a developing countries perspective (see Table 6).

Table 6. Levelized cost of electricity transmission ($LCOE_t$).

	Large scale	Small scale	Mini-grid	Off-grid
Typical generator size (kW)	50-300 MW	5-50 MW	5-250 kW	0.3-5.0 kW
Transmission costs	0.25 US¢/kWh (100 km circuit)	0.5 US¢/kWh (20 km circuit)	None	None

Source: [2]

Transmission and distribution (T&D) losses: In developing country situations, the losses in electric power output from generator to customer can vary from 10% in a well-designed and maintained power grid to 25% or more in an ordinary power grid.

Cost of distribution of electricity: The cost of electricity distribution mainly depends on the line length (circuit-km[5]) of the distribution conductors, and the size and number of distribution equipment installed. The levelized cost of electricity distribution can be calculated using Eq. 23 below.

$$LCOE_d = \frac{[C_T P_{PL} / p_f + x_d(a_{11}C_{11} + a_{2w}C_{2w} + a_{4w}C_{4w})](CRF_d + \beta_d)}{8760 \times P_{PL}\psi^{LF}} \qquad (23)$$

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[4] *Plant capacity factor* is the ratio of actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time.

[5] *Circuit-km* is the line length in km required for extending the grid electricity services.

where, $LCOE_d$ is the levelized cost of electricity distribution in US$/kWh; p_f is the power factor of transformers, C_T (US$/kVA) is the unit capital cost of distribution transformers; x_d (km) is the total length of the electricity distribution line (circuit-km); C_{11} (US$/km) is the unit cost of an 11 kV distribution line; C_{4W} (US$/km) the unit cost of a 3-phase 400 V line; C_{2W} (US$/km) is the unit cost of a 1–phase 230 V line; a_{11}, a_{4W} and a_{2W} are the percent fractions of the total length (circuit-km) for 11 kV, 400 V and 230 V circuits, respectively; β_d is the fraction of the total capital cost of the distribution system towards annual operation and maintenance; P_{PL} (kW) is the anticipated load in the village for which the distribution system has to be designed; and ψ^{LF} (%) is the load factor (LF)[6] in the village or cluster of villages which to be served by the new distribution network.

Cost of delivered electricity by grid expansion: The estimated total cost of delivered electricity $LCOE_{dl}$ (US$/kWh) by extending the grid in the remote villages can be estimated by summing up its components using the following expression:

$$LCOE_{dl} = LCOE_g / (1 - L_{t\&d}) + LCOE_t + LCOE_d \qquad (24)$$

3.4.3 Cost of electricity from off-grid options

The cost of electricity delivered from off-grid options ($LCOE_{dg}$) in the rural areas has been widely studied and reported in the literature. REN21 [88] has estimated the cost of the electricity supply by the most common renewable energy technologies in the rural areas. The ESMAP [2] technical report presents a cost review of a range of off-grid/mini-grid technologies covering a wider spectrum of capacities from 50 W to 100 kW. Several other studies have also presented site-specific levelized electricity supply costs for off-grid options in developing countries context [32, 89-91].

3.4.4 Critical line length (circuit-km) for grid extension

The critical grid extension line length can be determined by comparing the electricity supply costs by grid extension and off-grid options. The critical line length (or circuit-km) is the length beyond which a stand-alone or mini-grid system has a lower cost of delivered electricity than that of the grid extension. If the site requires less line length (circuit-km) than the critical length, then the grid extension appears to be more cost-effective than the off-grid

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[6] *Load factor (LF)* is the ratio of average load to the anticipated load of a power system over a period of time.

options. On the other hand, if the site requires more circuit-km than the critical length, then the off-grid supply options would be economically preferable. The critical line length (or break-even length), x_c (km), can be calculated for n different off-grid alternatives using Eq. (25).

$$LCOE_g/(1-L_{t\&d})+LCOE_t+\frac{[C_T P_{PL}/p_f+x_c(a_{11}C_{11}+a_{2w}C_{2w}+a_{4w}C_{4w})](CRF_d+\beta_d)}{8760\times P_{PL}\psi^{LF}}=LCOE_{dg,j} \tag{25}$$

For $j = 1, \ldots, n$, where j stands for the off-grid option among n different alternatives. Equation (25) shows that the delivered cost of electricity varies with the anticipated load-to-line length ratios (P_{PL}/x_d) for a local setting.

3.4.5 Multicriteria decision aiding tool

Multicriteria decision aiding (MCDA) is a methodology that helps decision makers (DMs) to choose their most preferred alternative from a discrete set X = $\{x_1, \ldots, x_i, \ldots, x_m\}$, where each x_i is measured in terms of multiple criteria (indicators). The methodology provides a decision model that combines the criteria measurements with decision makers' preferences to rank the alternatives. Most commonly, an additive utility function is applied [92].

$$u(x_i,w)=\sum_{j=1}^{n} w_j u_j(x_{ij}), \tag{26}$$

where x_{ij} is the criteria measurement of the i^{th} alternative with respect to the j^{th} criterion, and the partial utility function $u_j(.)$ transforms the criteria measurements to a scale from 0 to 1, where 0 corresponds to the worst outcome and 1 corresponds to the best outcome. The vector of weights w represents the DM's preferences. The weights are assumed to be non-negative and normalized. Therefore, the feasible weight space is $W=\{w\in R^n : w\geq 0 \text{ and} \sum_{j=1}^{n} w_j = 1\}$.

Given fixed values for x_{ij} and w, the utility function determines the rank of each alternative as rank(i,x,w) = $1+\sum_{k\neq i}\rho(u(x_k,w)>u(x_i,w))$ where ρ (true) = 1 and ρ (false) = 0.

However, in many real-life problems, preference information from multiple decision makers may be difficult to obtain, and most of the associated information possesses a degree of uncertainty or impreciseness. Sometimes preference information can even be missing. Also, if preference information can be obtained from the DMs, it is unclear how the preferences of several DMs that disagree should be combined. To overcome these limitations, Lahdelma et al. [93] developed the Stochastic Multicriteria Acceptability Analysis (SMAA) method. Among the different variants of the SMAA method, this thesis utilizes SMAA-2 (and its variant, SMAA-O, which can treat mixed ordinal and cardinal criteria) [94].

3.5 PV system integration into a rural electric feeder (Publication V)

Grid-connected PV has been identified as the fastest growing power generation technology in mitigating the ongoing supply shortage in developing countries [95]. In India, for example, a 2.12 MW grid-interacted PV power plant was installed in 2008, and an additional 5 MW project is under construction [96]. Grid-connected PV offers many advantages over off-grid PV supply, including no need for batteries and other related accessories [15]. Apart from its own generation, Bangladesh has also been purchasing fossil-based electricity from privately owned 'Independent Power Producer' (IPP) at a higher price for its national grid. As the purchasing price of electricity from IPP is high, it could be possible to produce electricity by renewables at a similar price. A study found that a 1 MW grid-connected PV system in Bangladesh has the potential to generate up to 1844 MWh of electricity annually [97]. This section briefly describes the methodology to perform viability analysis of a hypothetically integrated centralized PV system into a real rural electric feeder. The financial competitiveness of this integrated PV system is compared with fossil fuel based private IPP generation.

3.5.1 Optimization and financial analysis

To determine a PV system that best balances local needs, optimization between grid and PV system is required. Numerous articles have been written about the optimal economic design of components such as PV, Wind, Diesel and Battery [98]. HOMER, a system optimization tool can optimize both off-grid and grid-connected power systems for a variety of generation mix [99]. RETScreen, a clean energy project analysis software program developed by the government of Canada, was used to evaluate the financial viability of the systems [100]. The model's algorithms for financial evaluation are as follows:
Cash outflow, $C_{out,t}$ for year t.

$$C_{out,\mathrm{t}} = C_{O\&M}(1+r_i)^t + C_{per}(1+r_i)^t + D \quad (27)$$

where $C_{O\&M}$ is the annual operation & maintenance costs of the PV systems, r_i is the inflation rate, C_{per} is the periodic costs or credits incurred by the system, and D is the annual debt payment, while the cash outflow at year zero ($C_{out,o}$) is $C(1-f_d)$ if C (US$) is the total initial cost of the project and f_d is the debt ratio. Cash inflows, $C_{in,t}$ for year t can be calculated as:

$$C_{in.\mathrm{t}} = C_{ener}(1+r_e)^t + C_{GHG}(1+r_{GHG})^t \tag{28}$$

where C_{ener} is the annual income from energy selling, C_{GHG} is GHG reduction income, r_{GHG} is the GHG credit escalation rate, and r_e is the energy cost escalation rate. At year zero, the only cash inflow is the sum of incentives and grants it received. The net cash flow (C_t) for year t is $C_{in.n}$-$C_{out,n}$.

3.5.2 Applied data for the analysis

Solar data: Solar inputs data are taken as a monthly averaged daily insulation incident on a horizontal surface (kWh/m^2/day) from NASA's Surface Meteorology and Solar Energy (SSE) website [101] for the proposed site of Laxmipur (22.3 ° latitude, 91.8 ° longitude).

Load profile: The monthly averaged daily load profile for the year 2010 is taken from the Load monitoring center of Laximipur Palli Bidyut Samity (PBS) [102]. Hourly data for all 365 days are not available, so monthly-averaged daily load data was utilized to create the hourly data, adding a daily 10% and hourly 5% noise portion.

Rural Feeder C: A centralized PV system has been introduced into the 'rural feeder C' of the Laxmipur sub-station. The rural feeder is currently fed by a 10 MVA, 33/11 kV rural sub-station situated in the Mozupur village in the Laxmipur district (Figure 5). The substation is fed power from the nearest central grid, Maizdi (132/33 kV), through a 35 km long 33 kV power line, which is made of a penguin 4/0 stranded ACSR (Aluminium conductor steel reinforced) bare overhead conductor. The average power loss for this 33 kV line section is found to be 1.6% of the power flow through it. The backbone of the feeder comprises 19.29 km of 11.0 kV lines that serves electricity to 10,145 clients in 45 villages at 240-400 volts through several 11/0.240 kV distribution transformers. The peak demand of this feeder in summer is 2.3 MW (17:00-22:00) and in winter is 1.80 MW (18:00-21:00).

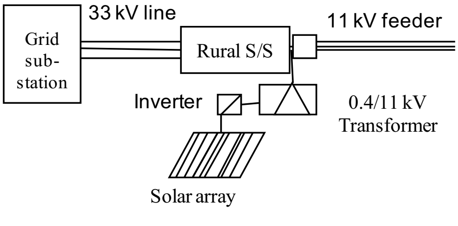

Figure 5. Grid-connected PV system.

The costs of the PV system and related parameters are presented in Table 7.

Table 7. Component costs and other parameters.

Parameters	Unit	Value
Per unit electricity price from IPP at rural sub-station	US$/kWh	0.210
Cost of PV cell	US$/$W_p$ [a]	3.5
Lifetime of PV cell	y	25
Annual operation & maintenance cost	US$/kW	0.71
Cost of Inverter	US$/Wp	0.21
Replacement cost of inverter	US$/Wp	0.14
Lifetime of inverter	y	10
Miscellaneous cost	% of initial cost	3
Installation and spare parts	% of initial cost	8.6
Inflation rate	%	5
Nominal discount rate	%	10
Derating factor	%	97
Cost of transformer, (0.40/11 kV, y-y)	US$/100 kVA	2 500

[a] W_p= watt peak

Sources: [89,97]

4. Results

This section presented question-wise results of five predefined research questions. This section first presented research findings on the issues related to grid-based rural electrification program. Then it presented findings related to evaluation and utilization of renewable resources to supplement those areas where grid extension is not viable. The resulted information are obtained through utilizing the methodological frameworks presented in section 3.

4.1 Driving and hindering factors and essential policy elements for a grid-based rural electrification program (RQ1)

This sub-section outlined the driving and hindering factors involved in on-grid rural electrification program and compiled the necessary elements to be integrated in the rural electrification policy to overcome the challenges. The key factors that determine the performance of rural electrification program, which were extracted from Bangladesh case and illustrated in light of generic rural electrification challenges, are presented below.

4.1.1 Driving factors

Prioritized system investment: Maintaining a priority to extend distribution lines is one of the challenges for a rural electrification program. Local areas that would appear to produce better revenues should be given priority for the financial viability of the program. Every year, sections of distribution lines are built because of political motives that are not justified on the grounds of revenue. This misallocation has been kept low by adopting a master planning system. Master planning is a clearly defined prioritizing process for line expansion based on anticipated revenue generation. By sticking with this priority model, BREP has been able to expand the distribution lines without undermining revenue preferences.

Community involvement: Community participation has been an important factor contributing to the success of rural electrification. Every electricity user is a member of a rural electric cooperative and has the right to be involved in the decision-making and policy-making practices. This membership practice gives the electricity users a feeling of ownership in the electric cooperative and encourages them to protect the assets from thieves and abuse. Electricity users have been educated by arranging village meetings and training programs about their responsibilities and the limitations of the power systems. Meetings with community leaders are also held to disseminate information on the key rights and responsibilities of the representatives. Rural industries, farming groups, and commercial leaders are also invited to the meetings to ensure that their interests are not ignored. House-wiring technicians are also selected from the local community so that they are easily available and trusted; this also helps reduce the wiring cost.

Anti-corruption features: Anti-corruption features are another success tool for Bangladesh's rural electrification program. Meter reading and bill collection are the major areas vulnerable to corruption and people trying to undermine the success of the electricity distribution systems [98]. The anti-corruption mechanism is equipped with selection, training, job contract, and cross-checking processes for meter reading and billing operations. Meter readers are carefully selected and trained before being put on a master roll contract by cooperatives. The meter reader's reports are entered by billing assistants into a system, and they are used to prepare the electric bills. The billing supervisors prepare a meter report register and cross-check the entry made by the billing assistants. The meter reader's reports are also cross-checked by the people who deliver the monthly bills. The number of bills and the kWh recorded in the electric bills must agree with the number of accounts read and the kWh posted on the meter book control sheet.

Performance-based incentives: In order to improve the technical, operational, and financial efficiencies and the quality of the services, a performance measure tool is introduced in the cooperatives. This tool, called the Performance Target Agreement (PTA), consists of a clearly stated set of goals. The agreement is also meant to guide the cooperatives in becoming more self-sufficient and providing better customer services. As a reward for reaching the targets, employees of the cooperatives get a bonus. Cooperatives that fail to achieve their targets face financial penalties. The PTAs are set by considering the overall status of the cooperatives. The PTA contains parameters that measure financial performance as well as technical and operational competencies.

System loss monitoring: System loss monitoring is another important feature implemented to improve the cooperative's technical performance. This measure enables the cooperative to make individual employees liable for losses incurred at substations, electric feeders, and line sections. The managers of the cooperatives are required to visit the meters on a regular basis and take readings from the substation power meters. All meters for industrial and other large-scale consumers must be read within three days of the substation reading. In addition to the substation meters, the cooperatives must place meters at all feeder outgoings and at intermediate positions for long feeders. These readings make it possible to monitor system losses and make the managers more accountable for carrying out their responsibilities.

Disconnection for non-payment: Payments and bills are quickly reconciled by billing systems. Meters are to be disconnected after two months of non-payment. The finance section of the cooperative prepares account lists for those who need to be disconnected. The disconnection teams promptly carried out the disconnection. To restore the service after disconnection, the charges along with all unpaid bills have to be paid [103].

Centralized supervision, decentralized operations: The BREP is characterized by centralized planning, design, and construction and decentralized operational responsibility. Centralized supervision enables the REB to monitor and evaluate the cooperatives' performance using standardized and objective tools. Decentralized operational responsibility through the cooperatives ensures that the right personnel are empowered to make day-to-day operational decisions [6].

Standardized procedures and practices: The REB has introduced a series of instructions on planning, engineering, administrative, and business procedures. They have consistently been put into practice throughout the entire program, covering all aspects of the development and operations of the electricity distribution system. Standardization ensures the quality of the operations and accelerates their growth, while giving operation engineers the opportunity to share technical resources [24].

Exclusion of political parties: To be an eligible candidate for being a representative in a cooperative (e.g., a director), one must not be an office bearer in any political party. This requirement has helped isolate the rural electrification cooperatives from general politics. This feature enables them to focus on economic, commercial, and technical criteria for determining new connections and limits the scope for political intervention [103].

Prohibition of unions (CBA), and hiring and firing: A law prohibits unions from becoming involved in cooperatives, although staff welfare organizations do exist. Unions involved in many other organizations in Bangladesh have a painful history of diminishing the performance of those organizations and offering shelter for corrupt staff and practices. This factor prompted rural cooperatives to offer no mercy to wrongdoers or for bad practices and instead to encourage good performance. The message "perform or be fired" sets the standard that employees must work hard and abide by the cooperative's principles.

4.1.2 Hindering factors

Institutional weakness: Institutional weakness has been the major reason for the deterioration of the rural electrification program, and this weakness affects other issues as well. The main reasons for the weakness are that the institutional structure makes the cooperatives unfit to defy political influence and maintain autonomy for the REP. Due to the institutional weakness, major donors feel reluctant to provide funding for this program until credible reform has been made. Bangladesh's REP has been enjoying a certain measure of autonomy, but it has failed to defend the cooperative from political pressure in many ways, such as by allowing it to defy master planning, to refuse to purchase non-standard materials, to refuse to protect thieves, and to stamp out corruption.

Power supply shortages: Like other developing countries, Bangladesh lacks the capacity for sufficient electricity generation, and thus there has been a huge gap between supply and demand. Although only a portion of the rural population has been connected to the grid, the demand is still largely unmet due to supply shortages. Rural clients in Bangladesh face a huge amount of load shedding within the range of 10-18 hours a day during the hot summer days due to national power generation shortages. Vigorous load shedding creates many problems, such as (1) decreases in collection rates, (2) increases in power theft, (3) lower staff morale, (4) decreases public interest, and (5) diminishes the reputation of the program. The power shortage problem hinders expansion of rural electrification in Bangladesh to a large extent.

Unrealistic power tariffs: Considering what rural clients can afford, the tariffs for the domestic loads have been set artificially low. The higher percentage of domestic loads with an unconvincingly low price prevents the BREP from achieving financial stability. Studies have found that if the electricity price increased to a realistic level, the households would still not be spending that much more money than they would for kerosene for lighting. Several studies of rural households have found that each household without electricity spends on average 2.85 US$ to 5 US$ per month for lighting. The average household's electricity consumption in Bangladesh per month is 64 kWh. This means the cost will not go beyond their spending limit if tariffs are increased to a realistic level.

Shortage of funding: Rural electrification in Bangladesh, like other developing countries, has been primarily supported by donor agencies. The international donor agencies prefer to support the renewable-based rural electrification program. Major donor agencies are reluctant to provide funding for the on-grid rural electrification program due to institutional weakness issues. As the development budget is hugely dependent on donors' funding, the donors' reluctance to invest in the program has meant that the annual budget has been cut, slowing growth.

4.1.3 Essential policy elements

Although globally, many rural electrification programs are struggling due to the lack of effective policy settings, a number of rural electrification programs have achieved remarkable success by employing a diverse set of program designs. This thesis observed that a rural electrification program requires some key elements to be integrated in the concerned policy settings. These policy elements guide the rural electrification program towards success through addressing distinct rural electrification challenges. The essential elements for rural electrification program, which are formulated in line with Bangladesh's experience and in light of generic rural electrification challenges, are presented in Table 8.

Table 8. Essential policy elements for successful rural electrification.

Policy elements	Challenges to deal with
▪ Transparent criteria for project prioritization based on: o Capital investment costs o Density of load and consumers o Contribution from local communities	♦ Selection of infeasible areas ♦ No priority for economic merits ♦ Lack of discipline in area selection
▪ Community involvement through o Community level meeting o Democratic participation o Hire wiring crews from local community o Village advisers o Training for the clients	♦ Right-of-way ♦ Thieving, cheating, and misuse of electricity and infrastructure ♦ Non-payment of bills
▪ Efficient billing features for o Effective metering and billing o Proficient recoding of electric bills, collection bills, and o Disconnecting services for non-payment	♦ Cheating ♦ Lack of commercial practices ♦ Higher system losses
▪ Separate implementing and supervising agencies	♦ Lack of accountability and efficiency in financial and management operations.

Table 8. (contd.)

Policy elements	Challenges to deal with
▪ Incentive provisions for efficient staff	♦ Inefficient operation ♦ Low staff morale
▪ Standardized procedures and practices: o Standard specification for materials and designs o Maximize single-phase design o Minimize low voltage line	♦ High capital cost ♦ High operating and maintenance costs ♦ Low load densities
▪ Professional management practices: o Disconnection for non-payment o Exclusion of political parties o Prohibition of unions	♦ Higher system loss ♦ Lack of sustainable business management ♦ Higher operation and maintenance cost ♦ Lack of customer service
▪ Smart subsidy: o Provide long-term soft loan	♦ Customers’ affordability is low ♦ Poorly administered subsidy
▪ Low connection fee o Spreading a portion of capital costs over the electricity price	♦ Up-front hindrance for a new connection ♦ Lower connection rate
▪ Customer feedback through village advisers	♦ Lower motivation to pay bills ♦ Customer dissatisfaction

4.2 Electricity generating potentials of agricultural residues (RQ2)

The thesis has assessed the potential of sustainable agricultural residues in five South Asian counties – Bangladesh, India, Nepal, Pakistan, and Sri Lanka by applying the methodological framework presented in section 3.2. The available residues from crops and livestock and their total electricity generating potential per rural household were determined. The electricity generating potential of these residues was determined considering their conversion through the Anaerobic Digestion process. The annual electricity generating potential per household in the five countries is depicted in Table 9.

Table 9. The electricity generating potential per rural household (HH) in five countries.

Country	Energy potential (thermal) from freely collectable agricultural residues (PJ/y)	Electricity generating potential (TWh/y)	Number of rural HHs (million) [104]	Average electricity potential per rural household (kWh/y)	Basic demand per rural household[a] (kWh/y)
Bangladesh	230	16.7	24.5	679	360 [105]
India	1570	113.0	138.2	820	365 [106]
Nepal	53	3.8	5.3	724	365[b]
Pakistan	282	20.4	16.4	1238	365[b]
Sri Lanka	22	1.5	3.2	479	360 [107]

[a] A hypothetical demand which is considered as a lifeline goal from off-grid renewable-based energy systems in rural areas.

[b] Author's consideration.

This result means that a significant amount of bio-resources are available from agricultural residues for modern energy applications in the selected South Asian countries. The estimated annual electricity potentials from the residues per household in Bangladesh, India, Nepal, Pakistan and Sri Lanka are much higher than the basic electricity demand of rural households.

4.3 Viability for serving clean-cooking and electricity loads through hybrid biogas and solar resources (RQ3)

4.3.1 Optimal system configurations

This thesis has determined the optimal configurations of the power generating components that match the energy demands (both electric and thermal) of three categories of households. The optimized system components, total annualized cost, annual electricity production, and biogas consumption for all three category households are presented in Table 10. The presented configurations are capable of serving both heat (for clean-cooking) and electricity to the households at an electricity price (*LCOE*) of 0.384 US$/kWh, 0.354 US$/kWh, and 0.341 US$/kWh, respectively, for HHC1, HHC2 and HHC3 without facing any capacity shortage. Biogas required by each household corresponds to 30 kg, 45 kg, and 56 kg cattle dung per day for HHC1, HHC2 and HHC3, respectively.

Table 10. System architecture for meeting energy demands for three household categories.

Household category	System architecture	Total annualized cost (US$/y)	*LCOE* (electricity) (US$/kWh)	Electricity production (kWh/y)	Annual biogas requirement (m^3/y)
HHC1	PV 0.2 kW Converter 0.3 kW DGE 0.6 kW Battery 1080 Ah, 6V Cycle charging	282	0.384	PV = 333, DGE = 461	449
HHC2	"	344	0.354	PV=333, DGE=670	657
HHC3	"	394	0.341	PV=333, DGE=817	828

This result means that a hybrid biogas and solar system can potentially serve both thermal (clean-cooking) and electricity loads in rural areas if households possess 3 to 6 cattle per household. The optimization results give that all 3 household categories require system architecture of same sizes. This is because, in the simulation search space, the minimum size of digester gas engine (DGE) system was restricted to 0.6 kW that resulted over sizes of DGE and batteries. The oversized DGE system forced the batteries to receive energy from both PV and DGE system. The oversized DGE system has a significant effect to increase the *LCOE* as it causes more losses due to bidirectional power flows in batteries and converters. Thus, availability of gas engine of size less than 0.6 kW would cause further decrease of *LCOE*.

4.3.2 Monetary saving by adopting new technologies

This thesis has weighted the saving in monetary terms for shifting from conventional fuels such as fuelwood, kerosene, and batteries to new fuel sources- solar and biogas. The annual savings for displacing the conventional fuels for HHC1, HHC2, HHC3 were found to be 309 US$/y, 381 US$/y, and 412 US$/y, respectively. HHC1 incurred a total annualized cost of 282 US$/y for new service, while it would save 309 US$/y, which means that the savings exceed the cost if HHC1 shifts its energy service from conventional to new technologies.

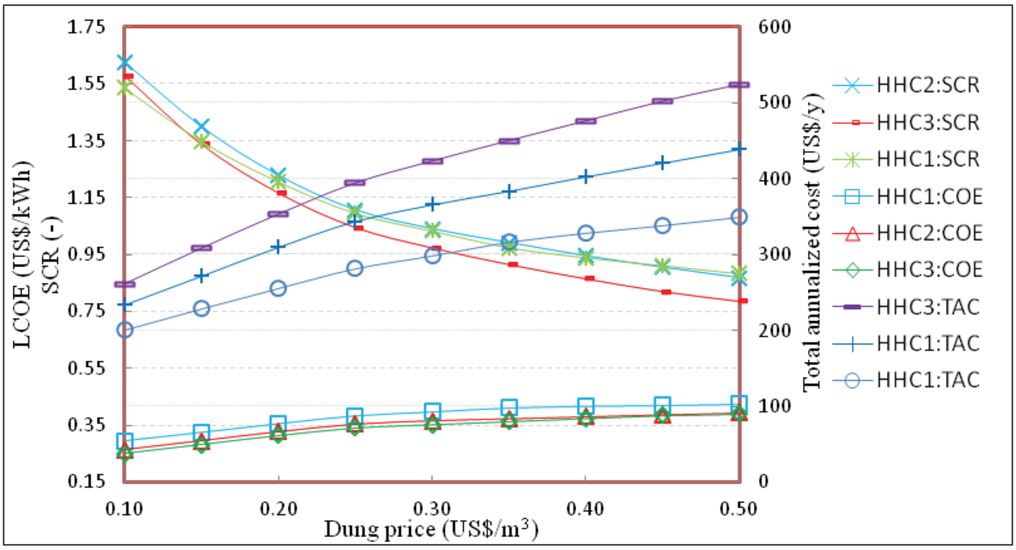

Figure 6. Variations in *LCOE* (electricity), *SCR* and *TAC* against various dung prices.

The costs and savings depend on the price of feedstock materials, which varies significantly in different circumstances. The total annualized cost (*TAC*) increases almost linearly with increases in the dung price, which results in decreases in the saving-cost ratio (*SCR*) (Figure 6). For example, for HHC2, the *TAC* is 234 US$/y for a dung price of 0.10 US$/m^3, while the *TAC* is 439 US$/y for a dung price of 0.50 US$/m^3, which yield SCR 1.63 and 0.87, respectively. This sensitivity results show that even at a higher dung cost (for example, 0.30 US$/m^3), the savings-cost ratios still remain more than 1 for the household categories 1 and 2. The *LCOE* (electricity) also varies significantly with variations in dung price. For example, the *LCOE* (electricity) is 0.263 US$/kWh for a dung price of 0.10 US$/m^3, while it is 0.39 US$/kWh if the dung price is set at 0.50 US$/m^3 for HHC2.

These results mean that the economics of the new energy services will still be better, even if households collect or buy dung at a slightly higher price as long as the energy consumption level remains the same.

The variation in current fuel prices (e.g., fuelwood) also has a significant effect on the annual savings and thus also on the savings-cost ratios. The SCR increases linearly with increases in fuelwood prices (Figure 7). For instance, the SCR is 0.82 for the fuel-wood price of 0.01 US$/kg and 1.21 for the fuelwood price of 0.07 US$/kg for HHC3. Thus, the trend of increasing prices for fuelwood (which is indeed the reality) makes the PV and gas engine hybrid system even more attractive in terms of monetary savings.

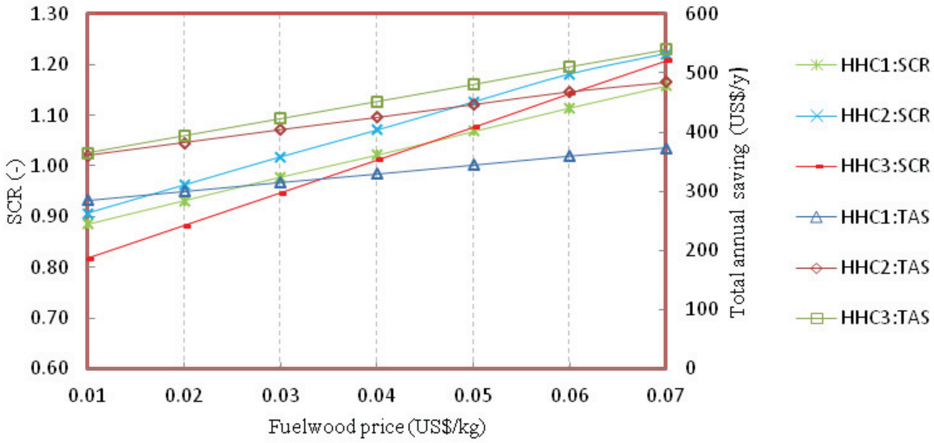

Figure 7. Variation in *SCR* with fuelwood prices.

4.3.3 Appraisal from ongoing biogas plants (from a practical case survey)

To validate the practical applicability of the biogas, this thesis investigated this matter through practical case findings from a questionnaire survey of 72 biogas plant households. The households' annual incomes varied depending on many factors, such as assets owned by the households, the nature of the livelihood of household members, and ownership of livestock. More than 70% of the surveyed households have an annual income of more than 1600 US$, and 21% have an annual income between 801 US$ and 1600 US$. About half (48%) of the households installed biogas plants to serve their cooking energy needs and get relief from problems related to collecting and burning biomass. About 60% of the households maintained that they have achieved time savings by installing biogas plants, and household members could spend more time with family members and guests. They also asserted that the use of biogas increased children’s spare time. Around 50% of the households observed that the biogas brought a positive impact on their health by creating a pollution-free environment in the kitchen and relieved their members from health issues such as inhalation, skin disease, fire accidents, etc., and improved their food habits and reduced health-care costs.

About 55% of the households expressed that the amount of biogas was sufficient to meet their cooking needs. Some households (27%) even maintained that the biogas amount was more than they needed. The households were also asked about their satisfaction with the biogas plant services. The majority of households (73%) were satisfied with the biogas plants. The survey also found that the households studied possessed an average of 4.5 cattle per household.

4.4 Choices of technology options for rural electrification (RQ4)

4.4.1 Critical length for grid line extension

This thesis has determined the critical line lengths (or circuit-km) against renewable energy technologies – solar PV, biogas plant, wind turbine, PV-wind hybrid, and non-renewable technology diesel generator by applying methodology described in section 3.4. The costs of delivered electricity by the grid expansion and off-grid technologies with various line lengths are depicted in Figure 8. The intersection points between cost of grid lines and off-grid technologies are the critical line length for grid expansion. For example, if a line section has a load factor of 50%, the critical grid extension length (circuit-km) for a 10 kW load will be 12.8 km at off-grid supply cost of 0.50 US$/kWh (solar PV).

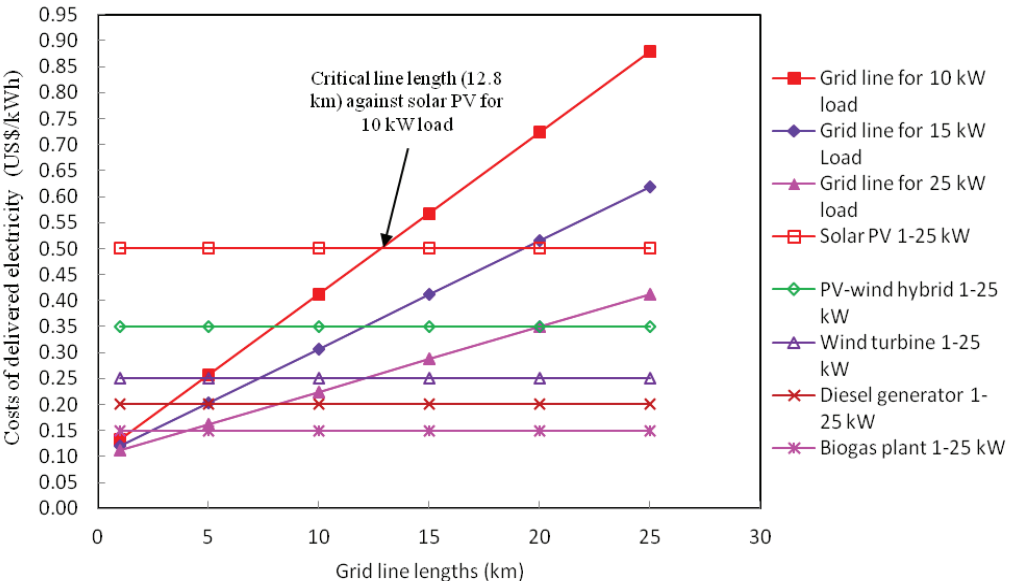

Figure 8. Critical line lengths for grid expansion against five off-grid technologies.

4.4.2 Critical load to circuit-km ratio

The *LCOE* for grid expansion is merely a function of the anticipated load to circuit-km ratio (P_{PL} / x_d), and therefore the viability of grid expansion against off-grid options can be represented by (P_{PL} / x_d) (Figure 9). The intersections between off-grid costs lines and the grid extension curves are the least anticipated load to circuit-km ratios for viable grid expansion against off-grid alternatives. For example, the cost line for PV-wind-hybrid (*LCOE*=0.35) and the grid extension curve for load factor 0.50 intersects at the point of anticipated load to circuit-km ratio 1.2 kW/km, which means that the critical line length against this off-grid alternative is 1 km if the line has an anticipated load of 1.2 kW and the critical line length will be 2 km if the line has an anticipated load of 1.2×2=2.4 kW and so on.

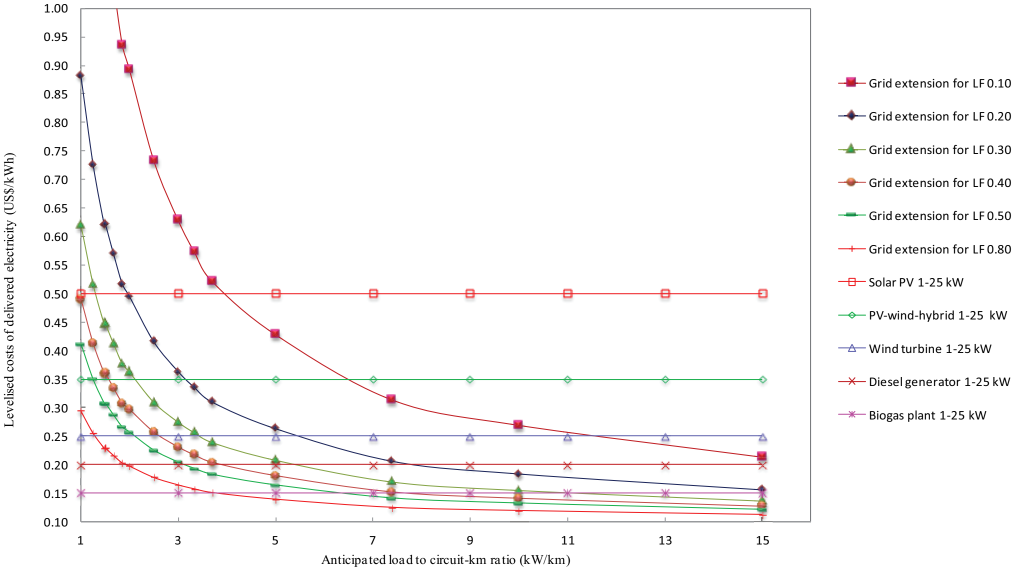

Figure 9. Anticipated load to circuit-km ratios (P_{PL} / x_d) against off-grid configurations.

According to the above analysis, the critical line lengths for the selected area (village) were found to be 1.8 km, 5.0 km, 7.8 km, 13.9 km, and 23 km against off-grid costs of 0.15 US$/kWh (biogas plants), 0.20 US$/kWh (diesel generator), 0.25 US$/kWh (wind turbine), 0.35 US$/kWh (PV-wind-hybrid), and 0.50 US$/kWh (solar PV), respectively. In fact, the village requires a 24.1 km line for supplying grid electricity services. Therefore, this village was found to be non-viable for grid expansion against all of the off-grid options.

4.4.3 Ranking of off-grid technologies

As grid expansion is not a viable option for the selected village, I have illustrated which off-grid options would be best suited in terms of five sustainability dimensions. After simulation with SMAA-O, it gives rank acceptability indices for all the alternatives (Figure 10). The rank acceptability indices show how often an alternative will get this rank with any preference weights. Figure 10 shows that solar PV and the biogas plant are the most attractive alternatives for the first rank (b1) with 59% and 41% acceptability, respectively. Among others, wind turbine, small-hydro, PV-wind hybrid, and diesel generator obtain zero acceptability for their first ranks. The alternatives other than solar PV and biogas plants are unlikely to be the most preferred alternatives, based on the assumed decision model.

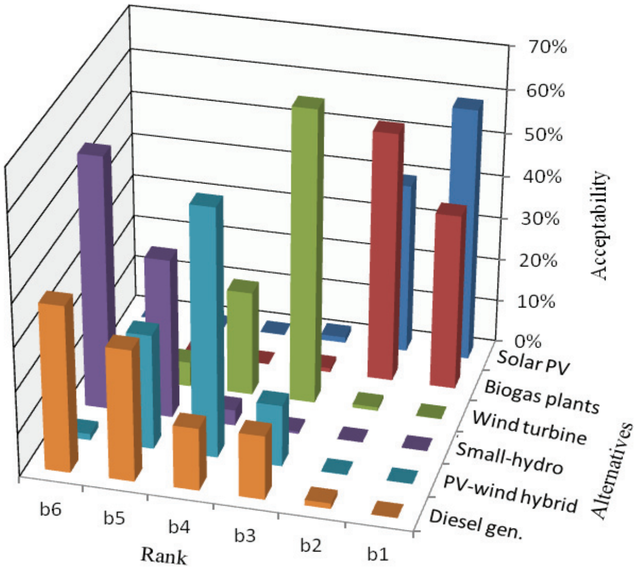

Figure 10. Rank acceptability indices.

The above rankings are obtained without any preference information, and therefore it is necessary to check that the preferences are agreed by the DMs. Figure 11 presents the central weights for the alternatives against all of the criteria. Figure 11 shows that the alternatives – solar PV and biogas plants – are favored by the weight preferences that are uniformly distributed among all five criteria dimensions. Solar PV and biogas plants look likely to get DMs' consent. The confidence factor is another term to check the acceptability of the results. It is the probability for an alternative to be the preferred one with the preferences expressed by its central weight vector. A high confidence factor indicates that the alternative is almost certainly the most preferred one. The solar PV system and biogas plant have obtained a good confidence factor, 98% and 87%, respectively. In contrast, diesel generator and wind turbine are possessed with low confidence factors, 10% and 4%, respectively.

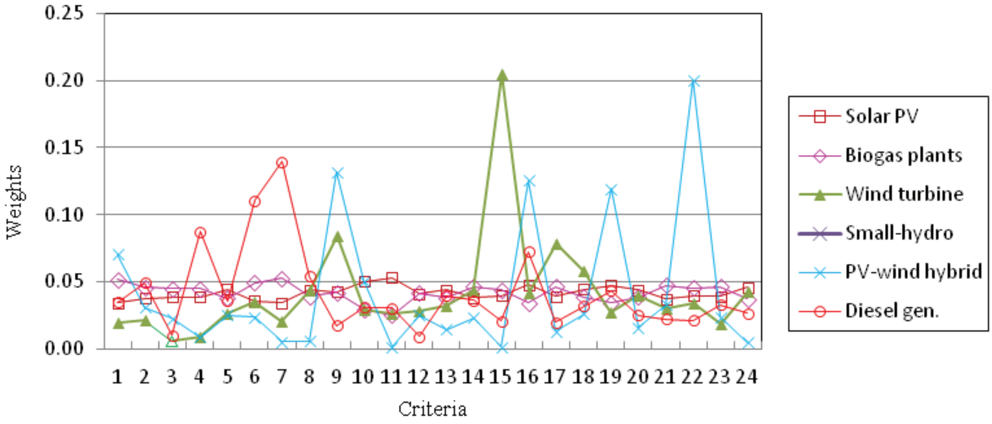

Figure 11. Distribution of central weights for efficient alternatives.

This above result means that the required length of the grid-line is more than the critical distances against all the off-grid alternatives. Therefore, the grid extension is no more a preferable (or exclusive) option to serve the studied village. The DMs might choose solar PV (best option) or both options (best and second best) for extending electrification to this village.

4.5 Economic viability of integration of centralized PV system into a rural electricity feeder (RQ5)

4.4.1 Economic indicators

The optimized PV system can generate 43% of the total electricity demand of the feeder against the current 40% shortfall at *LCOE* of 0.264 US$/kWh. The financial indicators- net present value (*NPV*), internal rate of return (*IRR*), benefit cost ratio (η_{BC}) and simple payback (*SP*) are obtained with this optimized PV system, while the PV energy selling price was set to 0.264 US$/kWh. The financial indicators vary strongly with the variation in the electricity selling price escalation rate while all other inputs are kept constant. *NPV* is found negative when the electricity price escalation rate was set to zero. The *NPV* seems to reach zero at 2.2% of the yearly escalation rate (Figure 12). The η_{BC} is also less than 1 for a 0% escalation rate, and it is found to be unity at a 2.0% escalation rate (Figure 12). The *SP* is 11.2 years against the project life of 20 years. These indicators mean that the project is profitable if at least the 2.2% electricity price escalation rate is considered.

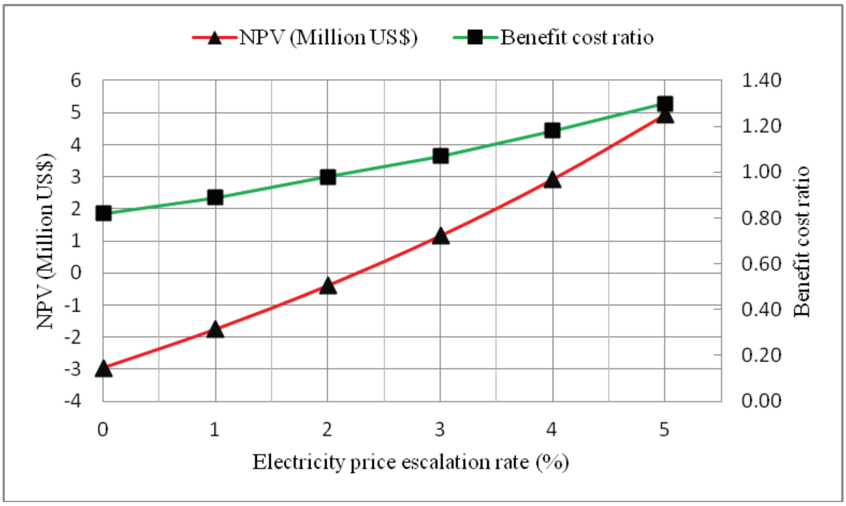

Figure 12. Economic indicators while electricity selling price was set to (0.264US$/kWh).

4.5.2 Viable PV electricity selling price

The *NPV* of the project was found to be positive when the PV energy selling price was set to 0.250 US$/kWh and electricity price escalation rate was fixed at 3% (Figure 13a). By including the benefit from the clean energy project, i.e., income from GHG reduction (e.g., 30 US$/tCO2e) [108], the project was found to be viable at the electricity selling price of 0.235 US$/kWh. This is only 10% higher than the current IPP purchasing cost (Figure 13b).

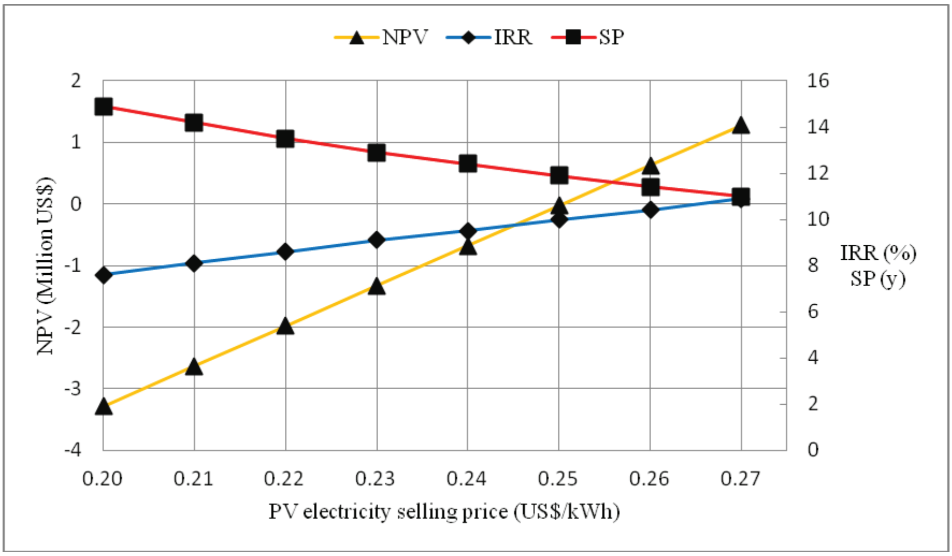

Figure 13(a). Indicators with respect to PV electricity selling price.

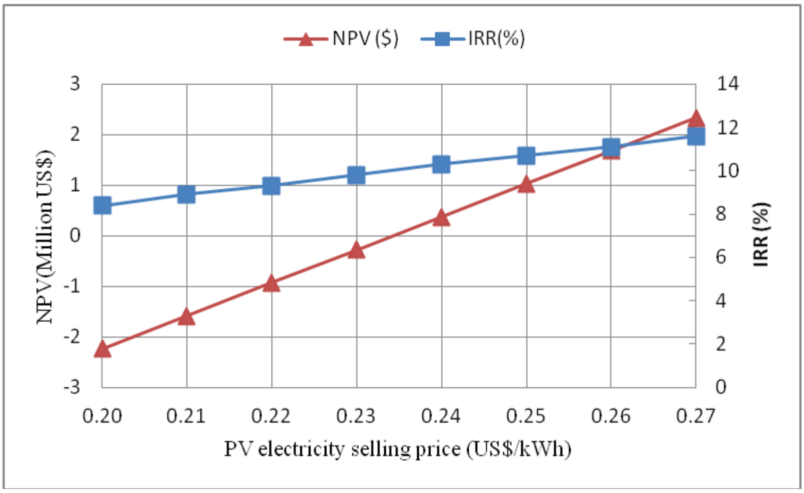

Figure 13(b). Indicators while the clean tech benefit was included.

Figure 13. Variation of economic indicators with the PV electricity selling price.

If the utility wants to buy electricity from the PV system at the same price as it purchased from IPP, the PV system needs a 5% electricity price escalation rate to make the *NPV* positive. The *IRR* and η_{BC} is 10.2% and 1.02, respectively, when the electricity price escalation rate was set to 5% annually. At this escalation rate, the PV system can produce electricity at 0.205 US$/kWh, which is less than the IPP price (Figure 14).The simple payback time now is 14.2 years.

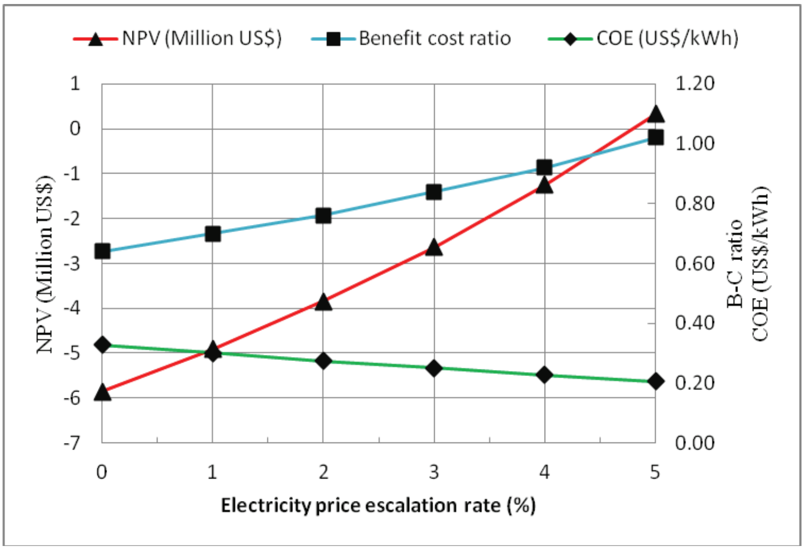

Figure 14. Visualization of economic indicators while the PV electricity price is the same as the IPP rate.

The results mean that, at the electricity price escalation rate of 5%, the PV system can produce electricity at a lower price (0.205 US$/kWh) than the fossil fuel based private IPP (0.210 US$/kWh). The economic indicators – net present value, cost of energy production, and benefit-cost ratio – all appear to be profitable for the project, while the electricity selling price was set slightly higher (i.e., 0.250 US$/KWh) at electricity price escalation rate of 3%.

5. Discussion

Rural electrification process, as a whole, poses more challenges in terms of policy and institutional requirements, selection of technologies, and capital financing than the urban electrification process. Amidst these challenges, there are few developing countries which have succeeded in this effort whereas many countries especially in South Asia and Sub-Saharan Africa having their progress very slow and the coverage remains low. This thesis examines the distinct rural electrification challenges, and factors remain behind the success and failure of rural electrification program. From the lessons of Bangladesh REP and in light of rural electrification challenges, it is evident that rural electrification program requires some key policy elements to make the program a success. These policy elements should be integrated into the concerned policy setting of rural electrification program. Despite these essential policy elements are derived from the lessons of Bangladesh program, common nature of these challenges validate them equally applicable for many other developing countries.

If rural areas are found unviable for grid expansion, then off-grid options should be taken into consideration. The thesis shows that deploying of renewable energy technologies are potentially viable option based on resource availability and techno economic merits for rural areas in many developing countries.

Significant amount of agricultural residues are available for electricity generation in South Asian countries. The assessment considers anaerobic digestion process (biogas plants) for converting residues into biogas because it is recognized as an environment friendly and cheap technology in rural context. These residues can be utilized for electricity generation to meet household-level basic electricity demands. The utilization of these residues proves financially attractive and they do not compete with other applications. Despite the data processing techniques and methodology are illustrated by utilizing data from South Asian countries, they can be generally applicable for any other developing counties subject to applying site specific residues characteristics values. The main challenge in applying this method is choosing or determining the appropriate characteristic factors data that vary significantly over geographic regions, harvesting practices, storage, ages etc. These presented data are obtained from available literatures sources and can be used for estimation of potentials of residue resources.

Site specific characteristic values are essential to plan and design a specific rural electrification project.

Conventional solid biomass based cooking is another problem in developing countries. Although biogas and solar resources separately cannot practically meet both cooking and electricity loads, their hybrid applications in households are very rare. Also these two renewable resources are abundantly found in rural areas and they are separately utilized by many households. This thesis shows that rural households can adopt biogas plants and solar photovoltaic together to realize both their clean-cooking and electric loads. This thesis considers animal manure for the feedstock of biogas plants by considering its widespread application. Whereas both crop and animal residues could even produce more biogas than this estimation.

Rural electrification decision choice needs to involve several sustainability criteria for their long term sustainability. The presented multicriteria-based methodology facilitates to select electrification options based on chosen sustainability criteria. This approach and data processing techniques can be applied in any site attributed by rural area. If the electrification decisions are made according to the predefined multiple criteria under all sustainability dimensions, their chance of failure will be minimized.

These methods and evaluation results can be sought by decision makers to upgrade the rural electrification policies and manage efficient, equitable and effective rural electrification program. By enacting proper policies and judiciously utilizing abundant renewable resources, developing countries can achieve electricity for all within an acceptable time framework. The major limitation of this thesis is that all the methodologies and tools are illustrated through Bangladesh’s case data, whereas data from other developing countries may give, to some extent, different outcomes.

6. Summary and conclusions

Many developing countries in the world, particularly in South Asia and Sub-Saharan Africa, have been struggling to accomplish rural electrification with having rural electrification pace very slow and coverage low. The rural electrification program of Bangladesh received a very distinctive status with respect to its representative features and its pioneer tackling of adverse socioeconomic conditions in developing country. Based on the Bangladesh experience and global-level success cases in developing country situations, it is evident that despite having varied socio-political situations among developing countries, rural electrification programs require some common elements to be included in their policy settings to make rural electrification program a success. The key driving factors for the success of Bangladesh program had to do with prioritizing system investments, community involvement, anti-corruption features, standardized practices and performance-based incentives while excluding political parties. On the other hand, hindering factors were found to be the lack of organizational autonomy, shortage of funding, unrealistic tariffs, and power supply shortages.

According to the estimation by the assessment method, a significant amount of bio resources are available from agricultural residues for modern energy applications in the selected South Asian countries. The estimated annual electricity potentials from agricultural residues in Bangladesh, India, Nepal, Pakistan, and Sri Lanka are about 680, 820, 720, 1200, and 480 kWh per household, respectively, and could be used to meet the basic electricity demand of rural households.

The lack of clean-cooking fuels is a major hindrance for billions of rural people in developing countries. Individual renewable resources alone cannot practically serve both clean-cooking and electricity loads. Biogas plants together with solar PV systems can potentially serve both thermal (clean-cooking) and electricity loads in rural households in Bangladesh if they possess 3 to 6 cattle per household. The households can achieve monetary savings of worth 309 US$, 381 US$, and 412 US$ per year for household category1, 2, and 3, respectively, which is more than their annual cost, with the aim of vastly improved services. The survey results from the studied households made it clear that the biogas technology offers many benefit to the users, and it is acceptable and within reach of many rural households. Almost all the households would be satisfied with the biogas plant if some supportive measures (e.g., warrantee, maintenance support, and marketing facility for manure) are taken by the biogas plant providers.

Rural electrification decisions are community conjugate process which need close focuses on all the major sustainability dimensions. Social and environmental factors are usually overlooked in the decision choice when selecting decentralized options, which makes them imprudent against environmental and community challenges. Multicriteria decision support for selecting the appropriate technologies would enable a rural electrification program to have safeguarded itself from these challenges.

Facing severe power crisis in the grid for many developing countries, the addition of electricity to the grid from integration of PV system can be a great step to reduce the supply shortage. A PV system was integrated into a real rural electric-feeder in Bangladesh, and the viability of the system was examined in terms of financial indicators. The analysis shows that the rural grid can produce electricity from PV systems at the same price the fossil fuel-based Independent power producers serve.

To sum up, a grid-based rural electrification program requires some key policy elements to be integrated into the concerned policy settings to overcome the distinctive rural electrification challenges. Developing countries can achieve efficient, equitable and effective rural electrification programs by enacting these elements into their policy. Renewable resources can potentially supplement rural electrification in many rural areas where grid expansion is not viable through judicious application.

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Access to electricity appears to be a prerequisite to materialize social, economic, and human development in the underprivileged rural areas. Still today, 1.1 billion rural people in the developing world do not have access to electricity. Only few developing countries have succeeded in rural electrification effort whereas many countries especially in South Asia and Sub-Saharan Africa are still struggling with keeping their electrification coverage very low. Although the rural electrification process poses more challenges than the urban electrification, rural areas are blessed with abundant and relatively evenly distributed renewable energy resources. This thesis explores the distinctive features of rural electrification task and present solution frameworks for sustainable and accelerated rural electrification for 1.1 billion people.

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