A decentralized energy option for rural electrification—Using polygeneration in India

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Electricity access is undeniably linked to equity and economic development especially among the rural communities. Clean cooking energy and safe drinking water are also essential for their socio-economic progress. When addressed in an integrated manner, interventions on these systems could have a wider impact. In this context, this study explores the feasibility and potential impacts of a polygeneration system that provides electricity, cooking gas and clean water to a rural village in India. Developed through a case study methodology, this thesis examines the potential of local resources for power generation and cooking. The system considers the use of electricity for water purification. With the help of a socio-economic survey and a field visit, the demand of electricity in the village is calculated. Based on the results from the resource estimation and demand survey, a polygeneration system with solar and biogas technologies has been designed using the techno-economic optimization software HOMER. The study also estimates ability and willingness to pay of the rural households for electricity. The willingness to pay estimate was based on a bidding game approach, and the influence of price and availability of existing fuels was also analyzed. Based on the existing socio-economic status and attitudes of the local population towards electricity use, potential impacts of polygeneration system on the lives of the villagers have been identified. The analysis concluded that a polygeneration system based on solar PV and biogas technologies is ideal for the village. The project has the potential to supply biogas to 60% of the households. The levelized cost of electricity from such a system is calculated to be $/kWh 0.262, about five times higher than electricity paid by users connected to the national grid. Yet, the system provides an opportunity to bring energy and clean water services to the village where grid extension is unfeasible due to the particular topography of the region. With access to uninterrupted electricity, cleaner cooking fuels and clean water, the villagers are estimated to primarily benefit in terms of health, education, income generation, safety, entertainment, and comfort.
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Executive summary

There is a formidable challenge faced by governments across the globe in providing their people adequate and affordable energy in a sustainable manner. This challenge multiples when looked through the prism of global climate change and increasing poverty. Countries like India need to sustain the momentum in their economic growth to eliminate poverty and achieve the millennium development goals. This warrants a steep increase in primary energy supply and puts tremendous pressure on the existing energy and electricity supply network, mainly in rural areas where the most marginalized people live. Therefore, rural communities tend to be the most deprived of this essential service.

In India, most marginalized communities are scattered across the hilly and heavily forested regions of the country. The interiors of these regions lack reliable electricity access and other basic infrastructure such as clean water and clean cooking fuel necessary for a comfortable human subsistence. They are also neglected in the implementation of key infrastructure and social development programs due to their remote and inaccessible terrains during most part of the year. Due to this, a conventional approach may not be feasible and profitable. Hence, a decentralized renewable energy system with an ideal mix of technologies and policy mechanisms can offset the issues concerned with conventional grid extension. This also helps to bring about a significant positive impact on the lives of the rural populace.

Along these lines, a system based on the principles of polygeneration offers an integrated approach to issues such as clean sustainable energy supply, and better quality of life. In this study, polygeneration is defined as the combined production of two or more energy services by maximizing the conversion efficiency according to available input resources and technologies. In this context, this study focuses on providing reliable and quality energy and services in a remote village in India under the umbrella of polygeneration, and assess its potential impacts on quality of life. The proposed system in addition to electricity, clean cooking fuel also incorporates a water purifier among others.

A multi-method approach has been adopted to develop this thesis. It is developed in the form of a case study using direct field observations, socio-economic survey, focused group discussions, mixed method analysis and HOMER to answer specific research questions towards achieving the objective. Initial research and literature review lead to the formulation of a socio-economic survey and a field visit. Based on direct observations and the survey during the field visit an initial energy and resource assessment was carried out in the remote village of Penikelapadu in India. The survey outcomes indicated that all the families in the village lie below poverty line and were either dependent on agriculture or were farm laborers for livelihood. The village lacked access to electricity, modern cooking fuels and clean drinking water. The primary fuel used for lighting is kerosene and biomass (collected from the forest) for cooking. Results from the resource assessment indicated that there was no potential for wind power generation. The only available renewable resources were solar and biomass. It was observed that the village had good population of cattle which indicated a good biomass resource. Calculations yielded a dung potential of 625 kg/day which transforms to 13961.25 m³/year of biogas. On the other hand a load profile for electricity demand was generated and the household cooking energy demand was also estimated. This indicated the daily average electricity demand for the entire village to be 36.6kWh/d with a peak load of 5.84kW and the yearly cooking demand to be 12702 m³/yr. The clean water demand of the village was estimated to be about 2340 l/day.

Based on the resource and demand assessment an evaluation of appropriate technologies for the polygeneration system was carried out. Taking into account factors such as dispatchability, scalability, reliability and availability a combination of solar PV and biogas digester - generator system were deemed appropriate for the village polygeneration system. Using HOMER a simulation of different system configurations was carried out to find the technically feasible solutions and optimal size of the PV array and biogas generator system based on the net present cost and levelized cost of electricity generated from the system. Post optimization the polygeneration system comprises of a 4.5 kW biogas generator and 2 kW PV
array and an ultrafiltration water purification system with a purification capacity of 700 l/hour. Further, a sensitivity analysis was carried out based on the future load projections and fluctuation of fertilizer prices which influence the availability of cattle dung in the village. This yielded a linear increase in the NPC and capital cost of the system while showing a decrease in the LCOE. Of the total biogas potential of 13961.25 m³/yr, the polygeneration system utilizes about 6215 m³/yr for electricity generation and the rest 7746 m³/yr can be supplied as cooking gas. However, based on the estimated cooking energy demand, this would only suffice 60% of the households in the village. Therefore, rest of the village can be provided with improved cook stoves which also helps in a gradual energy and technology transition from the present inefficient methods of burning fire wood for cooking.

Using the survey, ability and willingness to pay of the villagers for an improved and reliable energy supply network was also estimated. Employing the contingent valuation method, both subjective and objective measures of willingness to pay of the villagers was estimated. The observations concluded a linearity in willingness to pay with household incomes but showed a very significant difference in the percentage of monthly income spent on energy needs particularly lighting. It showed that lower income households spend a far greater share (18%) of their monthly income for lighting which exerts a tremendous pressure on their ability to pay.

The potential impacts this polygeneration system can have on the quality of life of the people was assessed by gaging peoples’ perceptions on the benefits of better energy access and other services provided. Their perception towards importance of electricity in children’s education, its role in improving their study time at home were gaged. The loss of livelihood or inability to generate additional income and the additional time available for women to perform household chores after dark was also measured. It was observed that majority of respondents indicated that there will be an improvement in children’s study time and expressed a perception of better opportunities for income generation with the availability of reliable electricity and clean energy. Majority of households also expressed an improvement in sense of security with better lighting around the households and community.

Based on the existing socio-economic status and the results obtained from the system design attitudes of the local population towards electricity use, the analysis concluded that a polygeneration system based on solar PV and biogas technologies is ideal for the village. The project has the potential to supply reliable electricity, clean drinking water to the entire population and biogas to 60% of the households. The levelized cost of electricity from such a system is calculated to be $/kWh 0.262, about five times higher than electricity paid by users connected to the national grid. Yet, the system provides an opportunity to bring energy and clean water services to the village through a decentralized system where grid extension is unfeasible due to the particular topography of the region. With access to uninterrupted electricity, cleaner cooking fuels and clean water, the villagers are estimated to primarily benefit in terms of health, education, income generation, safety, entertainment, and comfort.
1 Introduction

1.1 Background

Access to electricity is one of the most vital instruments for promoting economic growth and social equity. (Nivedita Thakur, 2011) Rural communities tend to be the most deprived of this essential service across nations. Rural electrification plays a pivotal role in bringing about direct and indirect economic and social benefits by enhanced livelihood opportunities, better health care and education. Poverty imposes an oppressive weight on India especially in the rural areas where 77 percent of the population resides. This poverty is in terms of both energy access and nutrition. The most marginalized people in India belong to the tribal communities, which account for nearly 8% of the total population, scattered in the hilly and heavily forested regions of India namely the Eastern and Western Ghats and northeast parts of India. The interiors of these regions lack the basic infrastructure necessary for a comfortable human subsistence. Due to the remoteness and inaccessible terrains during most time of the year, they are often neglected in the implementation of key infrastructure and social development programs. Although an extension of conventional grid may not be feasible and profitable at all times; owing to accessibility of the location, existing demand and population distribution, decentralized renewable energy options pitch in as a valuable alternative due to their scalability. These decentralized renewable energy options with the ideal mix of technologies and implementation mechanisms can offset the issues concerned with grid extension and bring about a significant positive impact on the lives of the population they are envisioned to cater. Small scale decentralized energy systems are most favorable because, extension of conventional grid to distant villages with fairly low demand involves large capital investments with a significant amount of transmission and distribution losses.

However a single renewable energy technology may not suffice at all times the demand of the region in question due to the intermittent nature of the resources. In such cases an integrated energy system with a combination of different technologies operating simultaneously, can solve the reliability issues arising out of using just one technology. Such systems in the absence of reliable grid electricity emerge as an advanced and sustainable solution for a disadvantaged region. One such-concept named polygeneration is part of research at KTH.

Polygeneration

In the following study polygeneration is defined as the combined production of two or more energy services by maximizing the conversion efficiency according of available input resources and technologies. Trigeneration systems, cogeneration systems and dual purpose power production and desalination plants are a few examples of the polygeneration systems. Often these systems comprise of water purification system critical for many rural development projects. They can work either autonomously or interconnected with a larger grid (George Kyriakarakos, 2011). Results from earlier research show that a polygeneration system is “technically feasible and most likely financially profitable”. (George Kyriakarakos, 2011) Following Figure 1 presents a schematic view of a typical polygeneration system. It can be observed that a diverse set of resources are consumed to produce a wide variety of products.
Polygeneration systems are usually designed to produce more than one product and often produce little residual matter. This technology has relatively advanced in the areas of chemical and energy production processes but is still underutilized. These systems allow the reduction of consumption of natural resources and energy there by providing a reduction of unit cost of final products and thereby reduction of environmental burden. (Luis M. Serra, 2008)

There are few projects conceived and being researched under this concept at KTH. One such system KTH is an Emergency energy module (EEM) for disaster situations which offers electricity, clean water and other essential services such as a heating or cooling through various renewable energy technologies bundled into a shipping container. Another project focused on this concept is the micro scale polygeneration project in Bangladesh which looks into the feasibility of generating electric power and production of arsenic-free drinking water using biomass resources.

In this backdrop, this following study focuses on providing reliable and quality energy in a remote village in India. In addition to this a water purifier is also incorporated into the polygeneration system design.

1.2 Objective and research questions

India, due to its lack of a focused approach towards formulation of a sustainable energy policy, capacity building, social engineering, publicity, access to financial resources and technology adaptation to local needs, has had limited success in disseminating and popularizing renewable energy (Nafisa Goga D’Souza, 2008). This current energy situation and subsequent environmental problems require the utilization of innovative, advanced and efficient energy conversion and integration of technologies (Luis M. Serra, 2008).

Bearing this in mind the ultimate objective of this thesis is to propose a polygeneration system that caters to the energy and clean water needs of a rural village in India.

In order to achieve this objective, the following research questions need to be answered.

- What are the energy and clean water needs of the people in the rural village?
- Can the existing locally available resources suffice the current levels of demand?
- What is the optimal system configuration according to the local demand and resource potential?
- What could be the potential impacts of the designed system be on quality of life of the population?
1.3 Methodology

This thesis is developed in form of a case study which provides a descriptive analysis of the research questions mentioned in the earlier chapter. A case study approach to these research questions helps to build knowledge by exploring the peculiarity and the uniqueness of the village. This thesis is developed by laying the ground work necessary by an extensive literature review, direct observations and semi structured interviews conducted during various phases of the work.

In the first phase of this study, the objective of the research was determined and the research questions were formulated. During this phase existing literature on rural electrification was reviewed to understand the concept of polygeneration and its relevance for this case study. After the formulation of research questions, a suitable village that fits the criteria of a rural, remote location was identified. This was done in close cooperation with a local NGO Laya. Based on the research questions a Minor Field Study (MFS –SIDA) was formulated to gather the required qualitative and quantitative data on existing energy usage patterns, clean water situation, available resources and attitudes of local community towards electrification. For the Minor Field study supported by KTH and Swedish International Development Agency a socioeconomic survey was designed. During the survey observations about the local conditions were made with the help of semi structured interviews with the villagers and other stakeholders like village elders and personnel from the local NGO and through direct observations.

In the second phase of the study, based on the data gathered and observations made during the survey, the choice of technologies for the system was decided and a polygeneration system was designed to cover the demand profile generated. The design and optimization of the polygeneration system was carried out in the widely used energy modelling tool HOMER.

Ultimately in the final phase, based on the information gathered from the socioeconomic survey and semi structured interviews with the locals, the willingness to pay for efficient and reliable energy services was estimated. Additionally the potential impacts of the designed polygeneration system on quality of life in terms of health, education, economic situation, life style and were also assessed.

1.4 Scope

This case study is specific to needs of the village Penikalapadu and the potential impact it can create at a micro level in the village. The village considered for this study is a typical remote tribal village in the Eastern Ghats belt of India and the results of this study may or may not apply to other villages elsewhere. The scope of this study lies within the assessment of local energy resources and its potential to suffice the needs of the villagers. The study emphasis the need for an integrated approach for rural electrification and also sheds light on the impacts it can create on the local population.

1.5 Organisation of the study

This study is divided into five chapters presenting the results from various phases of work.

Chapter 1 defines the basic research objective and scope of the research. It provides a definition of polygeneration system in context of this study. The chapter defines the research questions, methodology and the road map for the study.

Chapter 2 provides background information about the status of rural electrification in India and the associated policies. It also provides information on various rural electrification programs undertaken by the Government of India. It describes the institutional framework for the dissemination of electrification programs and the available concessions from the government.

Chapter 3 presents the rationale for case study and provides results of preliminary observations from the Minor Field Study (MFS). It discusses energy and fresh water demand of the village and gives an assessment of the locally available resources based on the survey and semi-structured interviews.
Chapter 4 presents a discussion and analysis on suitable technologies for the proposed polygeneration system for the village based on the findings presented in chapter 3. Energy modelling and optimizing tool HOMER is used to arrive at an optimum configuration of the polygeneration system.

Chapter 5 presents the results from the field survey and assesses the willingness to pay of the users and their ability to pay for the services offered by the polygeneration system. It presents an analysis and discussion on how the willingness and ability to pay are influenced by the perception of current expenditure on the energy services.

Chapter 6 discusses potential impacts the polygeneration system can have on lives of the population. It outlines the direct and indirect benefits from the services offered by the polygeneration system. The next part presents results from the field survey in which people’s perception about the benefits from better services are measured. Based on these results, the actual benefits and total impact of the polygeneration system is assessed.

Chapter 7 summarizes the research results while concluding that a polygeneration system is the ideal of the chosen location. It also presents an overview of the overall impact of polygeneration system on quality of life of the villagers.
2 India energy and rural electrification policy context

India, which is one of the populous and emerging economies of the 21st century, is the fourth largest energy consumer in the world after the United States, China and Russia. India has an installed electricity capacity of 211 GW and a major chunk of which is coal based generation of 57% and renewables accounting to mere 12% of the total installed capacity. The rest of the electricity mix is comprised of Hydroelectricity - 19%, Natural gas – 9%, Nuclear and diesel amounting to 2% and 1% respectively as illustrated in the figure below (Figure 1). It is estimated that in India at least one quarter of the population lacks access to electricity, while the electrified areas suffer from rolling electricity blackouts. Unlike in most developed countries where the energy demand had reached or is close to reaching a saturation stage, it should be noted that in India the potential energy demand is still unmet. (Graczyk, 2012) According to India Human Development Survey an overall household electrification is estimated to be 70 percent. While 94 percent of urban households had electricity, only 60 percent of rural households had access to electricity. (U.S. Energy Information Administration, 2013)

![Installed electricity capacity - India 2011](image)

The electricity distribution network in India is one of the most inefficient in the world with a national average distribution losses ranging from 25 % and up to 50 % in some states (Central Electricity Authority, 2013). Though the government policy looks to overcome these problems through large-scale conventional and renewable energy projects, there are several shortcomings in its implementation attributing to various reasons. Extension of conventional grid to remote places is hindered by the spatial distribution of households, monthly electricity demand of households, variability in demand and potential recovery of revenue of from households for the supplied electricity (Kapil Narulaa, 2012).

Government of India (GoI) recognizes that economic growth is being hindered as a consequence of energy poverty. Thus, rural electrification is regarded as the prime mover for development by the Indian policy makers making it equally or more important than energy security (Graczyk, 2012). In-spite of various policy interventions and subsidies by the federal and local governments over past two decades, one out of six villages does not have access to electricity even today. Unfortunately, these are also the regions where the poor of the country live in. This state of affairs is partly due to the ambiguity in the definition of village electrification in the policies implemented over the years.

The focus of rural electrification in India until 1997 was on “electrification for irrigation” to increase the agricultural output of the country. Only after this period the focus shifted to an equally important rural household sector.

Until 1997 rural electrification was defined as “a village is deemed electrified, if electricity is being used within its revenue area for any purpose whatsoever” (Electricity, 2013).
This definition was slightly modified and adopted after 1997 which stated “A village is deemed to be electrified if electricity is used in the inhabited locality within the revenue boundaries of the village for any purpose whatsoever” (Ministry of Power Government of India, 2006).

After the enactment of the electricity act 2003, it was further modified to be more target specific. According to this definition a village would be declared electrified if:

- Basic infrastructure such as distribution transformer and distribution lines are provided in the inhabited locality.
- Public places such as schools, hospitals/health centers, government offices, etc. are electrified.
- Number of households electrified is at least 10% of the total number of household in the village.
- The electricity supply is at optimum voltage for lighting during the evening peak hours. (Ministry of Power Government of India, 2006)

By providing clarity in the policies the government has been successful to an extent in the rural electrification projects. However, the percentage of households connected to the electrical grid remains low in a given village. According to 2011 census only 55.3% of rural households have access to electricity with a moderate 11.8% growth from the previous census year.

Prior to 2003 the power sector institutional framework was such that all the function of policy planning, policy formulation, regulation and transmission were all under the purview of the government. But after the enactment of the Electricity Act. 2003, while policy planning and policy formulation still remained with the federal government, separate entities were created for regulation, transmission & distribution under the federal and state governments. The Act seeks to provide an enabling framework for accelerated and efficient development of the Indian power sector, encouraging competition with appropriate regulatory interventions.

Figure 3 Key players and Institutional framework of Indian electricity sector (prepared based on (GoI, 2013) (Graczyk, 2012))
The planning commission working directly under the chairmanship of the Prime Minister essentially formulates the five year plans and monitors their implementation in consultations with the central ministries and state governments. Ministry of power (MoP) under the federal government is responsible for the perspective planning, policy formulation at the national level. It is responsible for the formulation of the national electricity policy in consultation with the state governments based on the optimal use of available resources including new and renewable energy sources. Figure 2 above provides an overview of the key players and institutional framework of the Indian electricity sector. The state governments have their own energy departments and have considerable responsibilities to manage the particular energy issues and market conditions. The MoP is also concerned with the approval of projects for investment decision, monitoring of implementation of power projects and administration and enactment of legislation in regard to the thermal and hydro power generation, transmission and distribution. ((NIC), 2013)

Rural Electrification Corporation Limited (REC) under the MoP is the nodal agency at the federal level to implement rural electrification programs. The corporation provides financial assistance to state electricity boards and rural electric cooperatives for rural electrification projects. It oversees the development and penetration of the projects being implemented all over the country and provides funding for the implementation of the various rural electrification schemes envisioned by the federal government. The National Electricity Fund, an interest subsidy scheme rolled out through REC to promote capital investment in the distribution sector has helped in the expansion and modernization of the distribution and transmission network across the country.

Over the years several schemes and programs were implemented by the Government of India to improve the rural electrification situation in the country. In most of the schemes rural electrification was bundled with other essential services necessary for rural development and which did not create the necessary impact at the grassroots level.

**Kutir Jyothi Program (KJP)** was started in the 1988 to provide single point light connections to all below poverty line households in the country. It provided 100% subsidy for one time cost of internal wiring and service connection charges and builds in a proviso for 100% metering for release of grants ((NIC), 2013). Though the program was initially successful, it has put a heavy burden on the utilities and the state government in terms of costs incurred in extension of the new lines and its upkeep. This has eventually led to the decrease in the number of household being electrified over the years. ((NIC), 2013)

**Minimum Needs Program (MNP)** provided 100% loan to the utilities and state electricity board for last mile grid connectivity and was devised to exclusively target states with electrification rate of less than 65%. The aim was to cover at least 60% of the villages in each state and union territories. However the actual achievement was much lower than expected.

**Accelerated Rural Electrification program (AREP)** covers the electrification of un-electrified villages and households by providing 4% interest subsidy on loans availed by the state governments under the Rural Infrastructure Development Fund (RIDF) from approved central financial agencies such as the REC and PFC. The program targeted a complete village electrification by 2007 and households electrification by 2012 which is still to be achieved.

**Rural Electricity Supply Technology (REST) Mission**’s objective was to achieve total rural electrification through promotion of decentralized renewable energy technologies as well as grid extension. It proposed an integrated approach for rural electrification and aimed to promote, fund, finance and facilitate alternative approaches in rural electrification. However due to a relatively high upfront costs for various technologies, small scale decentralized systems have played a peripheral role in achieving 100 percent village electrification. ((NIC), 2013)

**Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY)** is the flagship scheme launched by the government of India with a vision to achieve 100% electrification of all the villages and habitations in the country by 2012 and further extended by another five years. The scheme aims to provide electricity
to all households by creating the necessary infrastructure in the form of establishing “Rural Electricity Distribution Backbone (REDB) with at least one 33/11 KV (or 66/11 KV) substation in each block and Village Electrification Infrastructure (VEI) with at least one distribution transformer in each village/habitation”. It also envisions in creating a Decentralized Distributed Generation (DDG) systems where the grid is not cost-effective or feasible. This program positions rural electrification as a necessary component for broader human and economic development. It aims to provide uninterrupted 24 hours supply of electricity through grid extension to expand the ambit of industrial activity, quality and modern health care services to the interior rural parts of the country. (Ministry of Statistics and Program Implementation, 2013)

Most of the earlier mentioned schemes and projects launched by the government of India primarily focused on the extension of grid infrastructure to the rural areas to provide quality and uninterrupted power. However, it should be noted that extension of grid alone does not guarantee a reliable and daylong supply of electricity. These programs have laid inadequate emphasis on capacity building in terms of power generation. The role of renewable energy options was also not adequately stressed which clearly evident from the government’s major budgetary allocations awarded to enhancing grid connectivity in villages. Due to this, augmentation of supply is not in sync with kilometers of new grid lines added to the transmission and distribution network. The benefits of these rural electrification schemes can reach the last mile only if they are accompanied by distribution reforms and de-politicization of electricity tariff (Graczyk, 2012). All these factors along with bottle necks in the Indian coal supply network have widened the demand supply gap in the electricity sector.

Therefore, GoI in the latest of schemes such as RGGVY has laid emphasis on alternative approaches to rural electrification. It proposes the combination of central grid connections as distribution franchises and Decentralized Distributed Generation at a local level to tap the available renewable resources. The scheme also takes care of the financial and technical sustainability of the program by stating that “Electricity supplied must be paid for”. If widely replicated this scheme can reduce the burden on the electricity supply shortfalls and reduce the urgency of costly grid extension. (James Cust, 2007). However, the subsidy tap-in structure to promote DDG at village and local level are skewed towards public sector entities and not aimed at promoting competition among private and public agencies. This has resulted in very few installations in relation to the actual demand and a virtual nonexistence of a standardized project. Moreover, the heavily subsidized grid expansion and lower consumer tariffs associated with them are seen as a threat to existing and upcoming Decentralized Rural Electrification (DRE) units. Lack of liberal financial lending options due to associated and perceived social, economic and technical risks together with restriction of private ownership of assets of DRE based on current guidelines have also hindered in the expansion of DDGs in India. Additionally, the lack of inter-institutional co-ordination among the government agencies and various stakeholders at all levels has also played its role in dampening the investment climate in RE thus restricting the progress of decentralized energy systems.

Though India’s energy and electricity policy can be characterized by the its emphasis on centralized grid connectivity with huge T & D losses, inequitable rural and urban energy supply and heavy dependence on fossil fuels, there is a clear visible change in focus and shift in approach to its energy needs. In this stride, the ambitious National Solar Mission of India can be termed as fairly successful in overcoming the barriers to achieve total electrification. This policy or mission has tried to reverse the perception among the policy circles that a major barrier to large-scale dissemination of decentralized renewable energy solutions is the nascent technology in India and its cost.
2.1 Approach to estimate willingness to pay and potential impacts of polygeneration system.

2.1.1 Willingness and ability to pay

The vision for most rural electrification projects is ultimately rural development with special emphasis on poverty alleviation which can be achieved only with long term financial self-sustainability of the project. However, this proves to be a challenge owing to considerably high costs of services (Electricity, cooking gas, etc.) in comparison to the grid and more importantly legitimate issues such as typically low ability and varied willingness to pay among rural consumers. While rural communities tend to be at the bottom of the socio-economic ladder in comparison to their urban counterparts, there exists intra-community socio-economic disparities within a given community in the former. These disparities have a significant effect on the ability to pay for services of the rural consumers, not to mention the effect on demand. It is a prevalent practice that people/households belonging to the low income strata of a community/village use the cheapest available fuels which are often of very poor quality (energy conversion ratio), thus increasing their overall energy consumption. This represents a higher expenditure for the quality and quantity of services availed, thus sharing a larger portion of their household income for energy services. The choice of these kinds of fuels is usually governed by the income of the household, reluctance to switch to newer and efficient fuels due to deep rooted misconceptions and ‘apparent’ lower cost of the fuel unmindful of other hidden costs involved.

While ability to pay (ATP) mainly depends on the income of the household which is closely related to poverty, willingness to pay (WTP) depends on variety of factors including income level, price of substitute fuels, the level of electrification or scope for electrification, real or perceived availability of alternatives for electrification and primarily household budget for energy expenditure. (Zerriffi, 2011) In pure technical terms, willingness to pay is defined as the amount of income one is willing to forego to avail a particular service. It has found its application through cost benefit analyses in diverse sectors such as health care, water resources management, environmental regulation and energy. (Whittington, o.a., 1990), (David A. Schkade, 1994), (Gertler, o.a., 1990) WTP measurement techniques can be mainly classified into two categories i.e. revealed preference which is based on actual or simulated price response data and stated preference based on data derived from direct and indirect surveys popularly known as Contingent Valuation Method (CVM) or approach (Christoph Breidert, 2006). A classification of frameworks to measure WTP is presented in Figure 3 below.

Figure 4 Frameworks for methods to measure willingness to pay (WTP) adopted from (Christoph Breidert, 2006)
India like most other developing countries has a deeply regulated electricity market, where prices are controlled by various measures either on the demand side or supply side. These prevailing market conditions may not necessarily reveal the true preferences among the consumers. Therefore economists believe that revealed preference methods are not the ideal methods to estimate the benefits of electricity service improvement and consequently willingness to pay. (Herath Gunatilake, 2012) On the other hand stated preference methods are flexible and allow for description of service improvement, thereby enabling estimation of WTP for service improvement. (Herath Gunatilake, 2012) These methods are widely used for estimating WTP for a service in developing countries due to unavailability of credible data on preexisting market and response. A study conducted by World Bank on the impact of electricity policy reforms in agricultural sector in India acknowledges that CV approach has a potential advantage in predicting the behavior of farmers with changes in the policy without the need to extrapolate from the past behavior. (Bank, 2001) It goes on to state that, the success of the method in estimating the WTP depends on the extent to which the respondents are well informed and are able to assess the total value of electricity and services provided. (Bank, 2001) (Francesco Devicienti, 2004)

There exists extensive literature on WTP estimates in different countries where researchers have over the years tested this method of investigation. Using this method however has often resulted in the impressively large estimate of WTP according to (Daniel Kahneman, 1993). An estimate for willingness to pay for green electricity in rural Kenya by (Sabah Abdullaha, 2011) used the stated preference approach in two econometric methods (Non-parametric and parametric) and concluded that respondents are willing to pay more for grid electricity than for solar power and favored monthly payments over a lump sum payment. Another study by (Koundouri P, 2009) by using double bounded dichotomous choice elicitation format found out that, consumers in Greece were willing to pay a premium of € 8.86 in their bimonthly bill as premium for construction of wind farms. In Japan (Noboru Nomura, 2004) conducted a contingent valuation survey to estimate the WTP for renewable energy where consumers were willing to pay a flat surcharge of Yen 2000 on their monthly bill. A recent study conducted by (Kai-Ying A. Chan, 2011) in South Africa measures WTP in subjective and objective measures similar to (Sabah Abdullaha, 2011) and investigated the equivalence of both measures. The study goes on to conclude that “attitudes towards the environment increased the residents’ WTP but, these attitudes do not influence on the maximum amount the residents are willing to pay extra”.

In the Indian context, there is fair amount of research on measuring the WTP of the consumer for enhanced electricity supply but not exclusively for renewable energy systems. A study conducted by the Energy and Resources Institute (TERI) in New Delhi uses both the revealed preferences and stated preferences techniques and estimates the WTP of firms for improved energy supply. (TERI, 2001) The study was undertaken to provide insights to decision makers on perception of quality and availability of power supply as well as their WTP for improved services. The WTP is established based on a bidding game approach by presenting a hypothetical scenario of improved power supply. (Bank, 2001) Another study by (Herath Gunatilake, 2012) uses CV method in two elicitation formats namely bidding game and single bounded closed ended elicitation format to estimate the WTP in central parts of India. A study by (James Cust, 2007) estimate the WTP for electricity ranges between Rupees Rs.100 and 120 per month by using the both the CV and revealed preference method based on the monthly electricity expenditure. Therefore the literature points to CV methods as the preferable and widely used method of estimating WTP. Based on the initial review of the existing data for the village, both a subjective and objective measure of willingness to pay needs to be estimated which is further elaborated in the later sections of this report.

### 2.1.2 Potential impacts

The benefits of electricity and cleaner energy access are well established and documented around the world. Though the nexus may not be conspicuous, development often goes hand-in-hand with easy and adequate energy access. Electricity mainly is perceived as a modern source of energy, essential for development (UNDP, 2002). Its impacts can broadly be seen through direct and indirect benefits in the form of provision of more efficient lighting for rural families, easing the burden of household tasks, improving farm and
business productivity etc. However, it should be borne in mind that providing a few light bulbs may not always have the desired level of effect that policy makers and politicians anticipate. (UNDP, 2002)

To assess the benefits of electrification for a particular community, region or country it is important to understand the relatively complex linkages between rural electrification and other critical infrastructure such as roads and schools and the development outcomes associated with such infrastructure. This helps in evaluating the role of electricity in development priorities such as poverty reduction and income generation, though it’s a fairly complex exercise. For example, a school in the community would play as much important role if not more in improving the education levels of the children as electricity access would help children to study at home in the evenings. (UNDP, 2002)

There are very few empirical studies that provide a firm economic quantification of benefits from rural electrification as it may take decades to be realized as in the case of improved educational outcomes from better study habits, quantifying the perception of safety and health benefits. This is further complicated by other phenomena such as migration from rural to urban areas. Gathering substantive and reliable information from surveys is also a difficult task. (Peter Meier, 2010) According to previous World Bank and United Nations Development program studies, the most fundamental way to assess the impacts of rural electrification is to observe the changes formerly non-electrified households make as they gain access to electricity and other energy services. The underlying assumption in these studies is that, electricity is not demanded for its own sake but it satisfies demand for other goods and services at lower costs. The earliest approach by World Bank for estimating benefits for rural electrification involved estimating likely expenditures for electricity and other energy services as total consumer benefits. This was further modified to include savings resulting from fuel switching thus known to be the ‘avoided cost’ method. Another more improved method of estimating the benefits of rural electrification was developed by the World Bank over the past decade using the demand curve. (Peter Meier, 2010) A demand curve indicates, for each level of consumption, the amount the household would be willing to pay for that level of consumption. Assuming that this WTP is at least equal to the benefit received, the demand curve provides a measure of household benefit for each level of consumption. (UNDP, 2002) While these approaches have their strengths in empirical and demonstrable estimates of benefits of rural electrification, they share a common weakness in their inability to measure the intangible benefits such as the impacts of rural electrification on improvement in health, education and overall quality of life. (UNDP, 2002)
3 Case Study

3.1 Rationale for a case study

As stated in the earlier chapters, the traditional approach to rural electrification has always been extension of the electricity grid. This approach overlooks the specific needs and preferences of the community or population it is about to cater. It is a known fact that recent rural electrification projects have demonstrated and established a link between energy access and socio-economic development. Therefore taking into account the specific needs of different end-user groups, the impact of the project and its performance can be dramatically improved. (The International Bank for Reconstruction and Development / World Bank, 2003) Any rural electrification project should be designed in such a way that the services offered are not beyond the economic constraints of the rural poor. Else the project benefits may flow only to the rural elite. Therefore before proposing a polygeneration system for a rural village it is imperative to understand the specific needs of the people and it could also be interesting to assess the benefits this project could bring to the lives of the people it is designed to serve.

In this process, the requirement is to identify and assess daily energy and clean water demand of a village large enough to be served by the polygeneration system. Apart from assessing the demand, it is equally important to assess the resource potential available in the village to choose the best possible mix of technologies that suffices the local energy demand. Therefore this process was conceived and executed in three stages namely,

- Village site identification
- Energy demand assessment
- Resource assessment

The appropriate location or rural village for implementing the polygeneration is dependent on factors such as

- Electrification status of the village
- Distance from the grid
- Terrain and connectivity to the nearest town.
- Population and economic status of the village

Firstly identification of an appropriate village which lacked basic amenities such as reliable grid connectivity and access to clean drinking water was necessary. A village named Penikelapadu in the state of Andhra Pradesh in India that perfectly fits this criterion was chosen with the help of a local NGO Laya. Upon request Laya has offered its logistical support for this research. With more than twenty years since its inception, Laya has been working in the tribal areas of Eastern Ghats region of India. It is involved in promoting and local management of micro hydro, solar and biomass energy initiatives in communities experiencing a high degree of marginalization. The regional resource center of Laya is located 30 kilometers away from the village and is primarily involved in promotion of herbal medicine use and sustainable and energy efficient cooking technologies in the village.

Now, in order to assess the impacts of rural electrification through this polygeneration system, it is important to study the available resources, energy usage and expenditure patterns of the local population. It is also important to look into the aspects of attitudes of the local population towards new and renewable energy technologies, community engagement and the link between clean energy access and other rural occupations.

For this purpose, in line with the case study methodology a field study was designed and conducted in the chosen village. The objective of this field study was to get a firsthand experience of conditions of the local population and develop an understanding of the issues and problems encountered by them in fulfilling their daily energy needs. As part of this field study, a household survey was deemed necessary to obtain data about income, expenditure preferences, energy usage patterns etc. Therefore, a comprehensive survey questionnaire as shown in the Appendix was formulated covering all the requirements and objectives of this research. It was developed well before the start of the field study and designed in such a manner that the questions were direct and simple. This is important as the respondents belonged to a tribal community
where the education level is quite low. Once the questionnaire was approved by the principal guide, the actual survey was conducted with respondents from every individual household in the village. A field officer from Laya was assigned for guidance in the entire duration of the survey. The outcomes of the field survey are presented in the following sections.

### 3.2 General Characteristics

As earlier stated, an ideal location for the implementation of polygeneration system is identified as the village “Penikelapadu” in the state of Andhra Pradesh in India. The village lies in the remote tribal belt of Eastern Ghats region in India. It is completely surrounded by forests and situated on the foot of a mountain. The village is at a distance of about 90 kilometers from the nearest town Rajahmundry and 35 kilometers from the Mandal headquarters (administrative division). The village remains cutoff from the nearby villages during the monsoon due to flooding and overflowing streams nearby. It lies about 12 kilometers away from a commutable road. There are no public means of transport to the village. The only way to reach the village is by walk or a private vehicle/tractor.

During the visit, it was observed that the village is characterized by absolute poverty and lack of access to basic amenities such as electricity and clean drinking water. Though the villagers have drawn power lines from a nearby village at a distance of 7 km using makeshift poles, supply is of appalling quality with low voltages and rampant load shedding stretching for weeks in peak summers. All inhabitants of the village belong to a primitive tribe and mainly depend on cultivation of forest lands and minor forest produce collection. The population in the village is largely illiterate and is below the poverty line (a government of India economic benchmark and poverty threshold index to identify the individuals and households in need of aid/assistance for subsistence) and survive solely on revenue and articles earned from barter of their agriculture produce. The primary energy sources used in the village are biomass for cooking (often collected from the nearby forest) and kerosene for lighting. The village has been neglected for the implementation of various government schemes for rural electrification due to its inaccessibility and very low demand.

Table 1 General information of the village

<table>
<thead>
<tr>
<th>Description</th>
<th>Males</th>
<th>Females</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Literates</td>
<td>21</td>
<td>23</td>
<td>44</td>
</tr>
<tr>
<td>Illiterates</td>
<td>29</td>
<td>44</td>
<td>73</td>
</tr>
<tr>
<td>Main worker - Cultivator</td>
<td>36</td>
<td>31</td>
<td>67</td>
</tr>
<tr>
<td>Main worker - Agricultural laborer</td>
<td>4</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Non worker</td>
<td>10</td>
<td>32</td>
<td>42</td>
</tr>
<tr>
<td><strong>Total Population</strong></td>
<td><strong>50</strong></td>
<td><strong>67</strong></td>
<td><strong>117</strong></td>
</tr>
</tbody>
</table>

The village has a total population of 117 individuals spread across 31 households. The average family size is observed to be about four persons per household. The houses in the village are closely situated with groups of 8-10 and some houses are located close to the nearby stream. The men in the family are the cultivators and the women are engaged in collecting of firewood, cooking apart from helping in the cultivation. Table 1 presents a summary of the main demographics of the village.

It can be observed from the data that the number of females outnumber the males in the population. This is primarily because ‘polygamy’ is practiced in the region since generations. Agriculture is the sole livelihood here, and is mostly rain fed. A family holds a small pocket of land and usually produces one or two crops a
year. Most of the agriculture produce is used for family consumption and any surplus is bartered for other essential commodities in the nearby local markets.

Table 2 Distribution of respondents' according to level of education

<table>
<thead>
<tr>
<th>Education Level</th>
<th>Males</th>
<th>Females</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>University</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Higher Secondary</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Primary</td>
<td>4</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Illiterate</td>
<td>8</td>
<td>14</td>
<td>22</td>
</tr>
<tr>
<td><strong>Percentage</strong></td>
<td><strong>39.39</strong></td>
<td><strong>60.61</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Literacy which is one of the main foundations for robust social and economic growth, is found to be 38% well below the national average of 74%. This is mainly because of lack of proper education infrastructure available in the region.

During the survey, questions were posed to individuals from each of the 31 households in the village. The educational status of the respondents was quite poor and mostly illiterate. The level of education of the respondents is an important factor in the survey as the perception of people towards new technologies and ideas depends on the level of education. Educated individuals tend to be more open to change and encourage rational decision making. It could be important to see how the respondents based on their educational level respond toquires on changes in current energy lifestyle. The following Table 2 shows the education level of the respondents in the survey.

Table 3 Categorization of households based on electrification status and income

<table>
<thead>
<tr>
<th>Electrification Status</th>
<th>Income groups</th>
<th>No. of households</th>
<th>Average annual income (I)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-electrified</td>
<td>Low</td>
<td>25</td>
<td>I &lt; Rs 12000</td>
<td>80.6%</td>
</tr>
<tr>
<td>Electrified</td>
<td>High</td>
<td>6</td>
<td>I &gt; Rs 12000</td>
<td>19.4%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>31</td>
<td></td>
<td>100.0%</td>
</tr>
</tbody>
</table>

During the survey, data on the annual income of individual households was also gathered. From the data, it was observed that all households belong to “below poverty line” group. It is also observed during the survey that five of the households in the village connected themselves to the grid using make shift poles and electric lines with the help of local administration. Therefore, to get a clear picture of the benefits from electrification, the households have been grouped into two categories namely ‘Electrified’ and ‘Un-electrified’ households. A significant observation that was made during this survey is that, income of each electrified households was higher than any un-electrified household, though the lowest and highest income in the data set fell under the national benchmark poverty index. It is understood that this difference in the income among households is mainly due to the area of land owned by each household and size of household. The effect of other income generation activities is observed to be very small, as revenue generated from
them is quite low and seasonal. Table 3 shows the categorization of all 31 households based on the income and electrification status.

### 3.3 Energy Demand

It is very essential to gain information about the existing energy use and expenditure patterns of rural households to design policies and programs which help in raising the living standards and alleviate poverty. This information also helps in assessing the demand for modern energy services and enables the planners and researchers in determining the ability of the rural households to pay for these services.

It is a known fact that, total energy demand of an un-electrified rural village is dominated by cooking energy demand. This is not mainly due to lack of demand for lighting rather, cooking is an energy intensive activity due to the inefficient fuels and equipment used in the process. Demand for lighting and other electricity consuming equipment is relatively lower due to financial situation of the households who cannot afford to purchase such equipment.

During the literature review, it was found out that majority of the population in rural households throughout the country uses biomass for cooking. This is due to the poor economic conditions of the population and the easy and cost effective availability of other traditional biomass fuels. According to the latest census figures it is learnt that 85.7% of rural households depend on traditional biomass fuels for cooking. These are alarming figures, as these kinds of fuels have a direct impact on the health and standard of living of the populace using them. (Census of India 2011, 2012) It is also learnt that 43.2% of rural households use only kerosene for lighting.

#### 3.3.1 Cooking energy demand

The earlier stated trend is reflected in the surveyed village. It is observed that all the households in the village use biomass for cooking. The biomass mentioned here consists only of firewood (dried tree branches) and does not include any other form of biomass such as cow dung or agricultural waste. The use of only biomass for cooking is mainly due to the abundant and free availability of firewood from the nearby forests and hills. The cost and unavailability of other efficient fuels and cooking technologies such as LPG and energy efficient gas stoves is also a reason for this. Cooking is usually done on a simple traditional three stone stove which is very inefficient and produces a lot of smoke causing serious health problems for the locals. Although the locals are aware of availability of other efficient and clean technologies, they have not adopted them due to financial and supply constraints. Another important observation made during the survey is that, even though the locals own a considerable number of cattle that produce dung, none of it is being used for cooking or other energy conversion process. It is also the case with the agricultural waste being produced in the village, which is used as fodder for the cattle.

According to the National Sample Survey Organization, if firewood is the only fuel reported for cooking purposes, about 29.05 kg of firewood per capita per month is consumed in rural households in India (NSSO, 1997). This when compared to the data gathered from the village, the amount of total reported firewood used per capita per month is estimated as 39.5 kg. It is noticed that difference in consumption of firewood across income groups does not vary significantly. The excess usage of 10 kg can be attributed to over estimation of weight of firewood, cold weather condition prevailing during the winter month and excess usage due to the abundant availability of firewood in the locality.

#### 3.3.2 Electricity demand

The main necessity of electricity in the village is established to be for household lighting and comfort purposes such as fans. Another important and interesting demand for electricity in the village was electricity for agricultural pumps. Though none of the villagers had a pump in their farms, they expressed a strong desire to have one. Since the energy consumption of the agricultural pump sets is bound to be much higher...
than average domestic demand and because of the spatial distribution between each unit, they are left out of the assessment for other solutions such as a standalone solar pumping system. The primary lighting fuel in the village is kerosene which is supplied at a subsidized price for all families. Even though some of the families have access to electricity, they complained of rampant load shedding and appliance damage due to severe voltage fluctuations which resulted in economic losses and thereby forcing them to use kerosene for lighting. The demand for electricity has been assessed based on the survey questionnaire in which the villagers were asked about the number and preferential choice of basic electrical appliances and the number of hours of usage. This was cross checked with the households already having access to electricity and a daily household electricity demand curve was generated.

The villagers are in need of efficient lighting equipment and therefore, two CFL lamps of 11W each for 5-7 hours in a day depending on the season were considered necessary for each household. Almost all the households expressed a desire for a ceiling/portable fan due to the hot and humid conditions prevailing in the summer months and hence a fan for 12 hours of the day/night with a rated power consumption of 55W was considered in the demand. The villagers also expressed a desire for a TV (100W) or radio (25W) for not more than five hours in a day for either of the devices. Also included in the household demand is a load of 600 W for the pump for water purification system. The results of the demand assessment are presented in the following Figure 4. It can be observed that the peak demand is from 17:00 hrs. to 23:00 hrs. on an average day and almost no demand during the day. The low demand during morning and afternoon hours is characterized by daily occupations of the population. Most of the villagers venture out for labor works in the morning hours and return to farming activities in the afternoon. The peak during the noon is due to the use of TV’s and fans during lunch time. It is also observed that the daily average demand for the entire village is calculated to be 36.6kWh/d with a peak load of 5.84kW and load factor of 0.261. This very low load factor indicates the consumption of power is often not very high and the system may not run to its full capacity. This increases the cost of the system which is a given when designing for remote communities. (Gómez María F, 2014) However, these costs far outweigh the social and micro economic benefits which are attributed to access to clean and efficient energy.

![Total Demand (KW)](image)

Figure 5 Average Household electricity demand in a day (Prepared by the author based on the household survey)

### 3.3.3 Fresh water demand

Water is a basic nutrient of the human body and is a critical element needed for human subsistence. (Guy Howard, 2003) It is estimated that worldwide about 1.1 billion people do not have access to safe drinking water and 2.2 million people in developing countries die each year due to a lack of safe drinking water, inadequate sanitation, and poor hygiene. (World Health Organization, 2012) In India despite the growing
economy and standards of living, water insecurity and unsafe water remains a major cause of child morbidity and mortality. It is estimated that nearly 600,000 children under the age 5 have lost their lives due to water related diseases like diarrhea and pneumonia in India in 2010 and most of them in the rural areas. (UNICEF, FAO and SaciWATERs., 2013) The lack of easy access to clean water is often associated with women travelling long distances to fetch clean water for drinking and cooking. This involves a lot of time, drudgery and makes them vulnerable to various problems relating to security and loss of livelihood opportunities.

Therefore easy and affordable access to safe drinking water is also a basic necessity for a comfortable human subsistence. In this context India had made great strides in reducing unimproved water sources by implementing its flagship National Rural Drinking Water Program. The objective of this program is to ensure provision of safe and adequate drinking water supply through hand pumps, piped water supply, etc. to all rural habitations and households. This program ensures the supply of at least 40 liter per capita per day in the rural areas.\textsuperscript{1}

Under this program the surveyed village has been installed with a hand pump, which ensures adequate supply of drinking water to the village during the wet season. However, during the very hot summer months it is learnt that the water supply decreases and villagers fetch additional water from the nearby stream. According to the information gathered from the Ministry of Drinking Water and Sanitation, ground and stream water samples collected from and around the village have tested positive for above permissible limits of Escherichia coli (E-Coli) bacterium and the water is brackish at times. This bacterium though mostly harmless, may cause diarrhea, urinary tract infections and other infections. This situation emphasizes the need for a more safe and clean drinking water source. Since the water sources mentioned earlier are the only available ‘clean water’ sources in the village, there is a pressing need for water treatment and purification systems in the village.

According to world health organization standards, a person engaging in normal physical activity in above average temperatures requires about a minimum of 7.5 liters per day. To maintain a basic level of food hygiene and a cover basic hygiene of a normal person, the per capita per day requirement is about 20 liters (Guy Howard, 2003). Based on these estimates the total clean water demand of the entire village is calculated. In the estimation, the water requirement of all age groups is considered to be constant. Based on this assumption, the total clean water demand of the village is presented in Table 4.

<table>
<thead>
<tr>
<th>Population</th>
<th>Water need/capita/day [l]</th>
<th>Tot. Water demand/day [l]</th>
<th>Distance to fetch Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>117</td>
<td>20</td>
<td>2340</td>
<td>0.3 to 1 Km</td>
</tr>
</tbody>
</table>

There by it is estimated that the total daily clean water demand per day of the village is 2340 Liters. It is observed that the villagers have to travel a considerable amount of distance based on the location of the house to fetch water. This distance ranged from a few hundred meters up to about two kilometers.

### 3.4 Energy resources potential

Before any renewable energy project is implemented it is imperative to assess the amount of resources available in the project implementation area. This is necessary to design an optimum solution involving different technologies. A more sophisticated knowledge of available resources allows for greater and efficient utilization in a broader assortment of electrical, thermal and chemical applications. The village Penikalapadu and nearby villages and habitations having situated in the hilly and heavily forested region of

\textsuperscript{1}National Rural Drinking Water Program (NRDWP), Government of India; http://www.mdws.gov.in/NRDWP
the Eastern Ghats belt of India have good amounts of natural resources. The region due to its topography has good potential for micro hydro, solar, wind and biomass electricity production.

3.4.1 Solar resource

India being a tropical country enjoys good amount of sunshine throughout the year. In this context, India has huge potential of solar power generation. The average annual solar irradiation varies from 4kWh/m² to 7kWh/m² across the country. The programs initiated by the government over the past decade address the need to tap this potential to provide reliable electricity access to far and remote areas of the country. Under the flagship Jawaharlal Nehru National Solar Mission (JNNSM), the country has made concerted effort to tap this resource. In a short span of three years it has made commendable strides in developing its abundant solar potential. It has successfully reduced the cost of solar PV energy thus making it amongst the low-cost destinations for grid connected solar power in the world. (ESMAP- Wrold Bank, 2013).

Availability of about 300 sunny days in a year with an average insolation of 5.5kWh/m² makes the state (province) of Andhra Pradesh a suitable location for the installation of solar power projects. (Order, 26-09-2012) Data gathered from the National Renewable Energy Laboratory’s solar resource assessment data base for the project implementing village has shown the availability of good solar resource. It is noted that the average noon peak irradiance for the chosen location is 800 W/m². The average hourly irradiation computed for the whole year is plotted in Figure 5. It can be observed that the daily hourly household load is superimposed on the available solar resource plot. This gives an indication of the available resource in relation to the existing demand per household of the village.

![Available solar energy potential in Penikalapadu](https://example.com/solar-energy.png)

Figure 6 Available solar energy potential in 'Penikalapadu' (NASA-Surface Meteorology and Solar Energy).

It can be inferred from the earlier figure that solar resource alone can suffice the electricity demand of the village. However due to its intermittent nature, lower energy conversion efficiency and high initial capital costs, solar PV alone may not be a viable and cost effective option. Therefore it is imperative to investigate the potential of other locally available resources.
3.4.2 Wind resource

Behind USA, China, Germany and Spain, India is the fifth largest wind power producer in the world. Out of the total installed power for renewable energy wind power accounts for 69.65%. Most of the power produced is on a large scale and grid interactive. (Ministry of Statistics and Program Implementation, 2013) India has huge potential for both off shore and on shore wind energy which is yet to be fully realized. Most of the projects implemented or envisaged in this area are often large scale and grid interactive and seldom on a decentralized scale. One of the reason for this could be the extensive promotion of solar and biomass technologies by the government in the form of tax incentives and capital subsidies for decentralizes and rural village electrification applications.

Before installing a wind farm or a wind turbine at given location, an assessment of the available wind resource is necessary. Such an assessment aids in the understanding of the local wind dynamics of the location. (Ramachandra T.V, 2014) Wind flow is caused by the differential heating of the earth’s surface and is altered by the rotation of earth. It is further modified by the local topography. This results in annual, seasonal, synoptic, diurnal and turbulent changes in the wind pattern. (R.E Hester, 2003) Therefore in order to make a precise assessment of the available wind resource, measurements spanning duration of 10 years are necessary. However, measurements based on the GIS (Geographic information system) acquired over a short duration provide an overview of the potential. It also provides information about the seasonal variation which facilitates in improved wind power harvesting.

In the village preliminary area identification was conducted and data was gathered at two different locations using the NASA surface meteorology and solar energy resource data base. It was observed that the comparative variation in wind speed at both the locations was minimal and hence eventually one location was chosen for the final ‘Area Wind Resource Evaluation’. The average wind speed plot generated from the location is shown in the following Figure 6.

![Figure 7 Monthly average wind speed in 'Penikalapadu' (NASA-Surface Meteorology and Solar Energy)](image)

Data used for the above plot is a ten year monthly average of the variation in wind speed at the village. It is apparent from the figure that, the average wind speed throughout the year is not more than 3.8m/s. Most commercial wind turbines are designed for a cut in speed of 3-4 m/s and a rated speed starting from 10
m/s. Therefore, due this very less amount of wind resource, it is not feasible and profitable to use a micro wind turbine as part of the polygeneration system.

### 3.4.3 Biomass resource

Biomass based power generation systems can be a promising and reliable power source in rural India where biomass based fuels dominate the energy consumption patterns. Fuel wood, crop residues and livestock dung are the typical biomass fuels used in India. This resource is yet to be fully exploited for off grid and decentralized applications in the rural areas. Therefore in order to promote this route of power generation specifically in the smaller capacity ranges of 3kW to 20kW, Ministry of new and renewable energy sources has launched a scheme ‘Biogas based Distributed / Grid Power Generation Program’. The scheme provides central financial assistance apart from training and other technical support for the implementation and operation of the projects.²

Biogas can not only be used to produce electricity but can also serve the cooking energy demand, provided there is sufficient resource available in the location. To check the feasibility of such a system, firstly it is necessary to estimate the amount of gas that can be generated from the available resource.

During the field survey it was observed that 81% of the households in the village own at least two or more cattle. The dung produced by these cattle can be used to produce biogas through anaerobic digestion. The total amount of gas that can be produced is obtained by estimating the production of the dung per cattle head per day. According to (Khendelwal, 1986) and (Nijaguna, 2002) the dung production from various categories of domestic animals in Indian conditions is given in the following Table 5. The amount of collectable wastes and gas yield per kilogram of dung is also given in the Table 5.

Table 5 Potential biogas production from different feedstock in Indian conditions (Khendelwal, 1986) (Nijaguna, 2002)

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Availability [kg/unit/day]</th>
<th>Collectable [kg/unit/day]</th>
<th>Gas yield [m3/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle waste</td>
<td>10</td>
<td>5</td>
<td>0,36</td>
</tr>
<tr>
<td>(Khendelwal, 1986)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffalo waste</td>
<td>15</td>
<td>8</td>
<td>0,54</td>
</tr>
<tr>
<td>(Khendelwal, 1986)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piggery waste</td>
<td>1,3</td>
<td>0,3</td>
<td>0,18</td>
</tr>
<tr>
<td>(Nijaguna, 2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poultry waste</td>
<td>0,06</td>
<td>0,06</td>
<td>0,011</td>
</tr>
<tr>
<td>(Nijaguna, 2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human excreta</td>
<td>0,4</td>
<td>0,4</td>
<td>0,028</td>
</tr>
<tr>
<td>(Nijaguna, 2002)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Since most of the domestic animals owned by the villagers are either cows or oxen, they are pooled in to the category of cattle. Considering the total amount of cattle, the amount of dung and subsequently gas yield per day is calculated based on the information from Table 5. The amount of gas generation from the substrate (dung) can be calculated using the following equation

² Biomass power and cogeneration program; http://www.mnre.gov.in/schemes/grid-connected/biomass-powercogen/
Equation 1

\[ \text{Biogas (m}^3\text{)} = \text{Raw substrate (kg)} \times \text{Total Solid Content} \times \text{Gas-generation rate per unit of substrate (m}^3\text{/kg)} \]

The total solid content of the animal dung is considered to be 17% (Lucas, 1996)

Table 6 Daily biogas potential in 'Penikalapadu'

<table>
<thead>
<tr>
<th>Total Cattle</th>
<th>Dung [kg/day]</th>
<th>Collectable Dung [Kg/day]</th>
<th>Gas yield [m$^3$/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>1250</td>
<td>625</td>
<td>38,25</td>
</tr>
</tbody>
</table>

From Table 6 it can be noted, the biogas that can be produced from the available dung per day amounts to 38.25 m$^3$/day. When calculated over the year this amounts to 13961.25 m$^3$/year. It can be stated that the biogas resource available in the village is fairly low considering only animal manure. The resource may be even higher when the crop residue from agricultural produce of the villagers is included in the calculation. However, the villagers use crop residue as food for cattle and most of them were reluctant to contribute it for biogas generation. Therefore the total available biogas resource in village over a year is 13961.25 m$^3$ which can be conveniently used to generate electricity for the village. It would also be very beneficial if the surplus biogas can be supplied as cooking gas for the villagers.
4 Polygeneration system configuration

Once the assessment of the resources and demand in the implementation location are carried out, the next step is to decide the configuration and combination of technologies for the polygeneration system. However, when designing such a system for a remote village important parameters like technical and economic feasibility of the system should be taken into account. Technical parameters such as size (Rated generation capacity) of each technology, maximum capacity shortage and size of the storage system need to be optimized in order to effectively harness local energy resources and supply according to the demand. In addition to the technical parameters, economic parameters like initial capital cost, net present cost, operation and maintenance costs and importantly levelized cost of electricity (LCOE) (LCOE is defined as the average cost of useful energy produced by the system) should be taken into account while designing a polygeneration system (Galindo, 2014).

Based on the above constraints, an optimization of the system should be carried out. For this purpose a simulation tool which simulates the operation of a given energy-system to supply a given set of energy demands operating in hourly time-steps over a one year time period is needed for greater accuracy and reliability. Additionally, the tool should also have the capability of operation and investment optimization of a given energy system. (D. Connolly, 2009)

4.1 HOMER - a techno economic optimization software

HOMER (Hybrid Optimization of Multiple Energy Resources) is a micro energy system design tool used extensively among the research community. It was developed by the National Renewable Energy Laboratory at the department of energy in the United States of America. HOMER can evaluate a wide range of technology options with different technical and economic constraints which gives the project developer flexibility to optimize the system to attain technical and economic feasibility. (Lilienthal, 2005) Using the optimization and sensitivity analysis algorithms, HOMER allows the project developer to study the effects of resource availability and system costs on cost of electricity and profitability of the project in terms of possible grid extension.

HOMER performs the analysis in three stages namely simulation, optimization and sensitivity analysis. Firstly simulation, serves in determining the technical feasibility and lifecycle costs by modeling a particular system configuration for each hour of the year based on resource availability and hourly load profile. The system cost calculations account for costs such as capital, replacement, operation and maintenance, fuel and interest. Additionally, lifecycle cost serves as a convenient parameter to compare the different system configurations from an economic perspective. This provides an improved accuracy over statistical models that typically evaluate average monthly performance of a system. (Lilienthal, 2005) This process helps the developer to determine and understand in a longer period of time, the interaction or the behavior of a system configuration and its operating strategy in a given control setting. (AvFelix A. Farret, 2006)

In the optimization process, HOMER determines the best possible system configuration by optimizing user defined mix of components that the system should comprise which is, size or quantity of each component and the dispatch strategy the system must use. It allows the user to enter multiple values for “decision variables” such as size and number of power generation equipment and dispatch strategy. In this process HOMER simulates and generates a vast number of system configurations which are then ranked according to the total net present cost in the order of least net present cost system being the optimal system configuration. (AvFelix A. Farret, 2006)

Sensitivity analysis helps in assessing the effects of uncertainty or changes in variables over which the user doesn’t have any control. In the optimization process, HOMER determines the system configuration that is optimal under a particular set of input assumptions. Where as in the sensitivity analysis process multiple optimizations are performed under varied set of input assumptions. (Gonc, alo Mendesa, 2011) A sensitivity analysis reveals the vulnerability of the system to changes in the uncontrollable parameters such as, change
in quantity of resources (like solar irradiation, wind speed etc.) and price of fuels. One of the primary uses of sensitivity analysis is this aspect of the modeling where the system designer is unsure of an exact value of a variable. Sensitivity analysis also has an important application in evaluating the tradeoffs in the system configuration from an energy planner, market analyst and policy analyst perspective. (AvFelix A. Farret, 2006)

HOMER provides the flexibility to use both conventional and renewable energy technologies in its analysis. Its ability to perform sensitivity analysis on most input variables provides a functionality which most other tools lack (Gonçalo Mendesa, 2011). The choice of using homer in this case study can be justified by its ability to explore and respond to the following critical questions arising out of the analysis.

- Are the preselected technologies most cost effective for the present case?
- What is the optimum size of the components to install?
- What is the variation in economics of the project to dynamics of costs and load?
- Is there adequate renewable resource?

For its ability to address these very basic questions in a clear, fast and simplistic manner, HOMER was favored over other programs such as RETScreen which don’t perform a time series simulations and offer diversity in choice of technology options. (AvFelix A. Farret, 2006)

### 4.2 Technology Assessment

For a rural electrification application such as the present case, the primary factors influencing the combination of technologies to be incorporated into the system are

- Dispatchability
- Scalability
- Availability
- Reliability

Dispatchability is the ability to deliver power at precisely the desired time. It allows the system/technology to perform load following to generate power in times of high demand and high value. Most Fossil fuel based power generation options have high dispatchability but are high on operation (Fuel) and maintenance costs. However, renewable energy technologies with a storage backup (considerable autonomous days) can also achieve higher dispatchability offsetting the price of fuel in fossil fuel based power generation systems.

Scalability refers to the capability of a technology to scale up or down its generating capacity easily based on demand and location. Solar PV and other RETS offer great modularity which can be easily deployed in location. Availability of the technology in the market at reasonable cost and easy availability of know-how on operation and maintenance is also a very important factor when sustainability of the technology is considered. In the present application where, the technology is to be deployed in a remote area with inadequate connectivity to towns and cities, the availability factor is critical.

Reliability of a power generation technology can be termed as the number of hours it can provide energy to the system all through the year (Hugo Morais, 2007). Interruption may be caused by the downtime/repair time of the units or due to external factors relative to the generation installation. (Hugo Morais, 2007) Reliability can be two pronged, first is the resource used and second is the technology itself. Compared to fossil fuels most renewable resources have poor reliability due to their intermittent nature. However, this can be tackled by using hybrid systems which use more than one resource. RETs like solar have high reliability which can operate for years with minimal maintenance. On the other hand power generation systems running with fossil fuels require high and constant maintenance.

Table 7 explains the above mentioned factors in terms of the chosen technologies for the polygeneration project.
Table 7 Evaluation of chosen technologies for the polygeneration system at Penikalapadu.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Dispatchability</th>
<th>Scalability</th>
<th>Availability</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV</td>
<td>• Production is foreseen with a lower degree of assurance</td>
<td>• Can be easily scaled up or down depending on the power requirement.</td>
<td>• Technology is well established and easily available.</td>
<td>• Technology very reliable – operating life time of 20-25 years</td>
</tr>
<tr>
<td></td>
<td>• Storage system with sufficient autonomous days improves dispatchability</td>
<td>• Easy to install</td>
<td>• A normal electrician can perform the maintenance</td>
<td>• 300 clear sunny days in a year at the location – fairly reliable</td>
</tr>
<tr>
<td>Electricity from Biogas</td>
<td>• Stable production relative to demand but low degree of uncertainty due to seasonal variation and feedstock availability</td>
<td>• Can be cost effectively and easily scaled up or down by construction of digesters.</td>
<td>• Easily available, but not commercially established on a large scale in India</td>
<td>• Resource exists locally in the village</td>
</tr>
<tr>
<td></td>
<td>• Easy to install</td>
<td>• Simple</td>
<td>• Easy to maintain and repair</td>
<td>• Technology is simple and practiced worldwide.</td>
</tr>
</tbody>
</table>

Therefore, while determining the best combination there has to be a balance of the earlier mentioned factors in addition to other important factors like available resources and forecasted demand. As stated in the earlier chapters, the micro scale polygeneration project being developed at KTH includes RE technologies like Solar PV and/or micro wind turbine and a biomass generator. For the current village, based on the available resources, a solar PV system would be a feasible solution.

However, due to a very low load factor of 0.261 coupled with the usage of electricity mostly after sun hours demands a larger storage system to suffice the demand. This significantly increases the initial capital cost and also the operations and maintenance costs for the storage system. Therefore a combination of Solar PV and other technologies is a good alternative. During the resource assessment it was observed that wind speeds around the village are quite low averaging below 4 m/s, which is nowhere enough for power generation purposes using micro wind turbines. However, it was observed that the village has good biogas generation potential due to the ownership of good amount of cattle among the villagers. This makes electricity generation using biogas a promising option given the easy access to technology and support from the government in terms of capital subsidies. Therefore, a system comprising of solar PV and a biogas generator would be an ideal system for this village.

India has made great strides in the promotion of solar energy technology both in small and large scale electricity generation. Today, the technology is widely available in India with capital subsidies from the government for its deployment. Even though the maximum efficiency of PV panels is limited to 20%, electricity produced from it has zero net emissions making it one of the cleanest energy technologies in the world. Other advantages of this technology include, its ease to deploy and operate without any noise pollution and a greater operating life time ranging from 20 to 25 years with very low maintenance. The main drawbacks of this technology is that it depends on an intermittent resource, land occupation, and higher costs involved in the storage and conversion of electricity from DC to AC.
Though biogas generators are not widely used for community scale power generation in India, this technology offers an opportunity for the village. Though a remarkable feature of biogas plant technology is its operational simplicity, a host of chemical, microbial, engineering and socio-economic problems have to be tackled for its successful and prolonged operation. One of the serious limitations in successful operation of this technology is the continuous availability of feedstock, defects in construction and microbial failure in the digester. (Mital, 1997) However this technology uses available local renewable resources thereby reducing emissions.

Therefore based on the existing resources and demand, a combination of solar PV and biogas generator are considered suitable for the village polygeneration system. The system should be optimized in such a way that the initial capital costs and levelized cost of electricity are the least for the desired combination of the system.

### 4.3 Optimal system design using HOMER

As discussed in the earlier sections, HOMER determines the optimal configuration of a system based on the lowest Net Present Cost (NPC) of the system. This is based on the technically feasible solutions and simulation of operation of different system configurations. Now, in order to analyze the Net Present Cost of the system and the Levelized cost of electricity generated from the system, HOMER is presented with load data assessed in section 3.3.2. It was assumed that there will be no day to day random variability in the load and all are AC loads. Under this assumption a plot for seasonal variation in load is generated in HOMER which is depicted in Figure 7.

![Figure 8 Seasonal load profile of village Penikalapadu generated by HOMER](image)

The simulation process was performed with a basic configuration of solar photovoltaic system and a biogas generator system. Biogas generator system which is the primary electricity generating component includes the digester and gas holder system, which cannot be modeled in HOMER. However, while optimizing the system, the economics of the biogas generator were also incorporated in the analysis. Apart from the main power generation components, the system also comprised of a flooded deep cycle battery bank, and an AC-DC power converter. The basic layout of the polygeneration system is shown in Figure 8.
With the basic configuration of the polygeneration system determined, a system optimization with relevant cost data for individual components and total capital costs as input was performed. As mentioned in the previous section, HOMER optimizes a system by comparing the economics of different configurations to calculate the corresponding NPC and LCOE. For this purpose HOMER assumes that all prices escalate at the same rate over the project life time. In other words, inflation in costs can be factored out by using the inflation-adjusted interest rate rather than nominal interest rate. (Tom Lambert, 2006) Though government subsidies exist for establishing power generation systems in un-electrified areas or areas with poor supply, capital subsidies are targeted for individual technologies unlike for a hybrid or polygeneration system. Many authors have suggested discount rates ranging from 6% to 11% for analysis in various parts of India. (Balachander Kalappan, 2013), (Kundu, 2013) A conservative value of 10 % was assumed for the current analysis based on the literature review and the available capital discounts for solar and biogas technologies in India. The table below summarizes the system fixed capital costs and the yearly operation and maintenance cost of the polygeneration system. It should be observed that the project life time is assumed to be 20 years based on the life time of solar PV technology durability and the operation life time of a biogas production plant. The system fixed capital cost and operation and maintenance cost were approximated based on the prevailing market prices of local expertise needed for the maintenance of the polygeneration plant, costs involved in the feasibility studies, freight charges for transportation and manual labour costs in relation to the available resource potential.

Table 8 Polygeneration system economic inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
<td>10%</td>
</tr>
<tr>
<td>Project lifetime</td>
<td>20 years</td>
</tr>
<tr>
<td>System fixed capital costs (Kundu, 2013)</td>
<td>$1500</td>
</tr>
<tr>
<td>System fixed O&amp;M costs (Balachander Kalappan, 2013) (Kundu, 2013)</td>
<td>$/yr 200</td>
</tr>
</tbody>
</table>

In addition to the total system economic inputs, HOMER was also provided with cost of individual components and fuel properties. The capital cost, replacement costs and operation and maintenance costs of the PV panels and Biogas generator per kW rated power output were entered along with other technical
parameters of the technologies which is illustrated in the table below. The cost of the PV panels was obtained from an average estimation based on the prevailing market prices of PV panels in India and through literature review which includes the cost of connections.

The minimum load ratio of the biogas generator was set to 50% to enable it to run at optimal efficiency. The cost of the biogas per cubic meter was determined on the basis of the prevailing cost of dung fertilizer. In locations near by the village and some other parts of India, the cost of bio fertilizer from cow dung is observed to be around $2 per 50 kilograms. Based on this, cost of 1 cubic meter of biogas was determined. The capital and operation and maintenance cost of other components in the polygeneration system was obtained from the dealers of the respective components and is illustrated in Table 9.

Table 9 Cost of individual components in the polygeneration system.

<table>
<thead>
<tr>
<th>Solar PV system inputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital [$/kW]</td>
<td>929</td>
</tr>
<tr>
<td>Replacement [$/kW]</td>
<td>929</td>
</tr>
<tr>
<td>Operation and Maintenance [$/yr]</td>
<td>20</td>
</tr>
<tr>
<td>Operating lifetime</td>
<td>20 years</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biogas generator inputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital [$/kW]</td>
<td>1348</td>
</tr>
<tr>
<td>Replacement [$/kW]</td>
<td>500</td>
</tr>
<tr>
<td>Operation and Maintenance [$/yr]</td>
<td>0.06</td>
</tr>
<tr>
<td>Operating lifetime [hours]</td>
<td>15000</td>
</tr>
<tr>
<td>Heating value</td>
<td>20 MJ/kg</td>
</tr>
<tr>
<td>Density</td>
<td>1.12 kg/m³</td>
</tr>
<tr>
<td>Carbon content</td>
<td>30%</td>
</tr>
<tr>
<td>Sulfur content</td>
<td>0.06%</td>
</tr>
<tr>
<td>Price per cubic meter</td>
<td>$0.11/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery Bank</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital (1156 Ah) [+]</td>
<td>1050</td>
</tr>
<tr>
<td>Operation and maintenance [$/yr]</td>
<td>20</td>
</tr>
</tbody>
</table>

| Converter               |  |

-36-
4.3.1 Optimized system configuration

With the aforementioned technical details and assumptions for each component as input, several combinations and sizes of components were perceived to be technically feasible. All such systems (winning sizes of individual components) are tabulated in Table 10. It is observed that the increase in the PV component capacity increases the capital costs, thereby increasing the operation and maintenance cost for the storage system not to mention the system reliability. An increase in the biogas generator capacity increased the fuel cost. Therefore a balance of these factors was needed to choose an optimal configuration. The most technically feasible options were further evaluated based on the net present cost (NPC) and levelized cost of electricity and an optimum system configuration was determined which is presented in Table 11.

Table 10 Winning sizes for power generation components in polygeneration system

<table>
<thead>
<tr>
<th>PV Array [kW]</th>
<th>Biogas Genset [kW]</th>
<th>Battery Bank [Strings]</th>
<th>Converter [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>3.5</td>
<td>4.5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>4.5</td>
<td>5</td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 11 Optimum polygeneration system configuration from HOMER

<table>
<thead>
<tr>
<th>Component</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas generator</td>
<td>4.5 kW</td>
</tr>
<tr>
<td>Solar PV</td>
<td>2 kWp</td>
</tr>
<tr>
<td>Battery Bank</td>
<td>13.9 kWh</td>
</tr>
<tr>
<td>Converter</td>
<td>1kW</td>
</tr>
</tbody>
</table>

The choice of a larger biogas generation system is justified by the availability of adequate biogas potential in the village as assessed in the section 3.4.3. The electricity generated from each power generating equipment is presented in the figure below. It is to be observed that the chunk of electricity is produced by the biogas generator and PV system acts as support to the biogas generation system in the polygeneration module. The Figure 9 shows the average monthly electricity production of both biogas generator and Solar PV system over the available daily global horizontal radiation.
The economics of the optimum system is illustrated in the following Table 12. The costs mentioned in here indicate the costs over the project’s lifetime of 20 years. The levelized cost of electricity (LCOE) produced from this system is calculated to be 0.262 $/kWh with an operating cost of 2,096 $/yr. LCOE is a convenient metric to compare power generation technologies on the basis of weighted average costs (Galindo, 2014). It is the preliminary estimate of the minimum electricity price to be paid by the end users in order for the system to be cost effective. (Gómez María F, 2014)

Table 12 Costs of polygeneration system

<table>
<thead>
<tr>
<th>Cost type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital [$]</td>
<td>13,199</td>
</tr>
<tr>
<td>Replacement [$]</td>
<td>1,070</td>
</tr>
<tr>
<td>Operation and Maintenance [$]</td>
<td>11,261</td>
</tr>
<tr>
<td>Fuel [$] (Biogas)</td>
<td>5,820</td>
</tr>
<tr>
<td>Total Net Present Cost (NPC)</td>
<td>31,043</td>
</tr>
</tbody>
</table>

The net present cost of the polygeneration system is highly influenced by the size of biogas generator. This is because of the operation and maintenance cost of biogas generator are the highest of all components used in the system. The cost of biogas and the component replacements associated with the system also have a role to play in the high net present cost of the system. However, simulations run on different combination of systems revealed much higher net present cost and LCOE. A breakdown of net present cost of the final system by cost type and component is shown below.
4.3.2 Grid competitiveness and system sensitivity

After determining the LCOE and net present cost of the polygeneration system, a sensitivity analysis was carried out to assess the effects of uncertainty in the system. The price of biogas, domestic load and the share of PV in the total electricity generated, were taken as variables for the sensitivity analysis. The choice of these variables is encouraged by the fact that, dung is used as fertilizer and its need and demand may subsequently increase the price at which the dung is procured from the villagers. With access to electricity, there is bound to be an increase in the load due to greater awareness of uses of electricity in daily activities, hence the increase in load was thought to be an imperative part of the sensitivity analysis. Another variable is the share of electricity form PV system. Limited availability of dung for biogas and unavailability of any other renewable resource for electricity generation in the village was the reason to incorporate the effect of increased PV generation on the economics and configuration of the polygeneration system. The values used for the sensitivity analysis are tabulated below.

Table 13 Inputs for sensitivity analysis

<table>
<thead>
<tr>
<th>HH Load [kWh/d]</th>
<th>Biogas2 [$/m³]</th>
<th>Min. RF [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.4</td>
<td>0.11</td>
<td>0</td>
</tr>
<tr>
<td>46.08</td>
<td>0.22</td>
<td>30</td>
</tr>
</tbody>
</table>
4.3.2.1 Effect of increased load

The effect of increased load on the optimal configuration was assessed by creating an additional load scenario by increasing the load by 20%. The optimal configuration resulting from this scenario was that of PV and biogas generator system with slightly larger capacities. A linear increase in the initial capital and NPC costs of the system was observed with increasing load during the sensitivity analysis as depicted in the Figure 11 below. Interestingly a decrease in the LCOE was observed in the system with higher load, emphasizing the need for higher load factors for RE projects to be economically viable. The observed LOCE for the base load case is $/kWh 0.262 whereas for the increased load scenario it is $/kWh 0.256.

![Figure 12 Effect of increased load on the polygeneration system costs](image)

4.3.2.2 Influence of cost of biogas

Varying the cost of biogas fuel for the polygeneration system did not yield any changes in the system configuration for the base load scenario. The cost was increased by 50% to 0.22 $/m³ from 0.11 $/m³ keeping in mind the exponential rise of fertilizer prices in Indian domestic market over the past few years. The scenario as shown in Figure 12 resulted in a significant increase in the NPC and LCOE with the initial capital cost remaining the same. This is mainly due to the fact that, bulk of the electricity generated by the system is from the biogas generator.

![Figure 13 Influence of price of biogas on the polygeneration system.](image)
4.3.2.3  **Effect of increased PV generation**

As resulted in the first scenario, HOMER also listed an optimal configuration of PV (3.5 kWp) and biogas generator (3.5 kW) for this case. While there was almost 30% increase in capital cost, the NPC increased by only about 6% in this scenario. Having said that, the LCOE of the system increased by about 10% compared to the base case scenario. It should be noted that even a marginal increase in LCOE for the system may not be financially affordable for the rural poor. Therefore, any increase in the LCOE in the system is considered to be an unfavorable outcome.

4.3.2.4  **Grid competitiveness**

Traditionally, standalone rural electrification systems are installed in remote areas far away from the grid. In this context, Break Even Grid Extension Distance is a reliable parameter to assess the cost effectiveness of standalone system, ignoring all practical considerations. Although COE from hybrid/polygeneration system could be greater than the COE of the grid, utilities charge by kilometer for grid extension. Therefore, as the distance from the grid increases, the cost of electricity from the grid also increases. (D.B. Nelson, 2005)

This COE electricity from the grid is only the apparent cost of supply considering the huge subsidies allocated for grid extension and other benefits. If the real COE from the grid is to be estimated then, costs for transmission, distribution, unaccounted transmission and distribution losses, fuel subsidies ought to be considered. In addition to these, opportunity cost for unmet energy demand by virtue of load shedding, cost of de-electrification (The phenomenon of de-electrification is the theft of wires, poles and even transformers where power supply does not exist, despite being connected to the grid.) and environmental costs further escalate the real COE from the grid making not as cheap as it appears to be. (International Market Assessment India Private Limited, 2006)

HOMER while finding the optimal configuration also estimates the breakeven grid distance, which is the distance from the grid which makes the net present cost of extending the grid equal to the net present cost of the stand-alone system. For the present analysis based on the prevailing market prices and conditions, the average COE from the grid according to the price fixed by the state electricity board is $/kWh 0.025 (Pradesh, 2013). This includes the large variation in generation costs on account of fuel used, location, efficiency, etc. Other parameter such as capital cost per kilometer of grid extension and operation & maintenance costs were based on a study by (International Market Assessment India Private Limited, 2006) which amount to $/km 8265 and $/yr/km 135 respectively.

![Figure 14 Breakeven grid distance for the polygeneration system](image-url)
From the results of the simulation and optimization process represented in the Figure 13 it has been observed that, the system achieves a breakeven in the costs against a grid proximity of 1.67 km. This means that, for a village at a distance of 1.67 km from the grid, the polygeneration system costs will be same as that for extending the grid and beyond that distance, grid extension becomes more expensive than the polygeneration system. The current village ‘Penikalapadu’ lies at a distance of about 15 km for the grid which makes the polygeneration project very suitable for this location.

4.3.3 Status of Biogas utilization and delivery of other services

During the resource assessment, total biogas production potential in the village from just cattle manure is calculated to be 13961.25 m³/yr. However, for the purpose of electricity generation 6215 m³ biogas would be consumed per year. This leaves a surplus of 7746 m³/yr. As stated in the earlier chapters, one of the purposes of this polygeneration project is to provide the village with clean and efficient cooking fuel. Keeping in line with this idea, average biogas requirement for cooking per capita per day in Indian conditions is estimated to be 0.3 m³ (Marchaim, 1992). Based on this estimation, total biogas demand for the entire population of the village amounts to 12702 m³/yr. However, the available 7746 m³/yr biogas will not suffice the entire cooking demand of the village. One solution for this is to utilize the crop residue from the agricultural produce in the village to include in the biogas production. However, most villagers own very small patches of land and grow only one or two crops a year. Moreover, many villagers have expressed reluctance in contributing their agricultural wastes to the project. Therefore, the solution to include agricultural waste for biogas production may not result in higher biogas yields.

Another solution could be to initially supply biogas to households having a relatively high willingness as well as the ability to pay and the rest of the population could be supplied with efficient cook stoves. This helps in maintaining a healthy balance of economic sustainability and desired outcome of the project. Therefore, households with annual income higher than Rs 6000 constituting 60% of the total households will be supplied with biogas for cooking. The rest 40% can be provided with efficient cook stoves as shown in Figure 14 Usage of Biogas for electricity generation below. This helps in a gradual energy and technology transition from the present inefficient methods of burning firewood for cooking. And in due course of the project implementation there is bound to be an improvement in the social and economic conditions of the people using efficient cook stoves. This may lead to an increase in aspirations and demand for a further better technology and fuel. Therefore, gradually the rest of the population in the village will also be provided with an improved service of biogas. The following figures illustrate the usage of biogas for different purposes and the services provided.

Figure 15 Usage of Biogas for electricity generation

As mentioned in chapter 3, the conditions prevalent in the village are such that the desired quality of water can be obtained without using complex and relatively expensive technologies like reverse osmosis and membrane distillation. In this case, an ultrafiltration system serves the purpose as the water samples showed
no contamination of deadly impurities like arsenic but tested positive for above permissible limits of *Escherichia coli* (E-Coli) bacterium and brackishness.

Ultrafiltration uses hydrostatic pressure of a liquid to separate higher molecular weight impurities across a semipermeable membrane. Due to the higher molecular weight of the impurities, pressure across the membrane becomes insignificant. The required hydrostatic pressure difference is attained naturally by gravity which in turn can be attained using an electrically driven pump. Therefore, as mentioned in chapter 3, the consumption of electric pump is accounted for in the load calculation.

The ultrafiltration system called SkyHydrant Water Filtration Unit used in this polygeneration system is a low pressure, high flow unit manufactured and supplied by sky juice foundation. It can produce up to 700 liters of clean water per hour which is much more than the actual demand of the village. Therefore, all the households in the village can be supplied with clean drinking water. The breakdown of distribution of various services to the villagers is illustrated in the figure below. As explained earlier, electricity and clean water can be supplied to the entire village but for the availability of biogas resource, initially only 60% of the village can be supplied with cooking gas.

![Figure 16 Distribution of various services to households](image)
5 Ability and willingness to pay

Though there is sufficient evidence to establish the relation between household income and primary energy consumption in a rural community, it is fairly difficult to judge the willingness to pay (WTP) for additional or better quality services due to regulated market conditions in most rural energy sectors where prices are highly controlled by direct & cross subsidies and influenced by a wide range of factors. These barriers combined with subsidies to conventional fuels and lack of awareness of cleaner and efficient technologies hinder dissemination of cleaner, reliable and sustainable technologies for rural electrification. (Akanksha Chaurey, 2010) Therefore for policy and feasibility purposes it is relevant to understand the importance of how much extra users are willing to pay for improved energy access.

While WTP and ability to pay (ATP) are interlinked, the difference in both parameters attains clarity when looked through the prism of perceived benefits for improved energy access among the customers. This means, WTP may be higher among economically disadvantaged consumers in the anticipation of a better quality of services and life even with a lower ATP. Whereas WTP may be lower even with a higher ability to pay among economically stable consumers. (Zerriffi, 2011) Ability to pay in its simplest terms can be defined as “the share of monthly household income spent on utility services such as fuel/electricity for lighting and cooking” (Samuel Fankhauser, 2005). This can more often accurately be expressed as a share of utility payments in the total household expenditure rather than total income as various informal activities provide a substantial share of household income (Samuel Fankhauser, 2005). However, due to scattered income generation and self-production of food grains and milk has made it difficult to assess the income expenditure pattern on different household necessities. Therefore the former approach of measuring ATP as a share of monthly income has been adopted in this study.

From the household income levels shown in Table 3, it is evident that 80% of the families in the village have an annual income of less than (Rupees) Rs 12000 ($200). This reflects the economic status of the population in the village which is below the poverty line. The remaining 20% of the households have an annual income of more that Rs 12000 and less than Rs 30000 ($500) which is still below the poverty line. To measure the ATP for electricity and other services, the threshold needs to be defined to determine what constitutes an acceptable level of expenditure for electricity and other services. Bearing complications relating to various sources of fuels used for one particular service many governments and international financial institutes have developed ad hoc rules on what constitutes an acceptable level of expenditure on energy (Samuel Fankhauser, 2005). According to World Bank, WHO and IPA energy a minimum acceptable level of monthly expenditure on energy/electricity is 10 % of the total monthly income. (Samuel Fankhauser, 2005) (The Insolvency Service of Ireland (“ISI”), 2013) Incidentally, the average monthly expenditure for lighting among the low income households in the village was calculated to be 10.5%. It has be noted that, all households are supplied with only 2 liters of kerosene per month and this results in lower income households spending a sizeable share of their monthly income for kerosene primarily used for lighting. This range of monthly income expenditure in low income households varies from lowest of about 4.1% to as high as 48 %. Similarly for the higher income households in the village availed both the subsidized supply of kerosene and electricity for lighting which amounted to a monthly expenditure of $ 2.4 per month. The average share of monthly income expenditure for lighting in this income category is 7.5 % with the two extremes being 4.5 % and 10.3 %. An interesting observation to be made here is that the lower income households spend a far greater share of their monthly income for lighting, even though it is of very poor quality.

Based on the learnings from the existing literature, it is evident that CV methods are the most preferred and widely used for the measurement of WTP. Based on its simplicity to apply and availability of data concerning the village a CV approach was designed which was part of the larger survey questionnaire. The intention was to measure both the subjective (perception and attitude) and objective (monetary) parameters of willingness to pay. Objective measurement was conducted using the bidding game format where the consumers, were given their total monthly expenditure on lighting or electricity as the least bid and asked how much extra they would be willing to spend every month for a continuous and better quality of
electricity. Hence, the initial bid for the lower income household was Rs. 50 and for the higher income households it was Rs. 150. Based on this method, the WTP of each household was estimated. In the measurements a tendency to overstate the WTP which is more than the ability to pay was observed. When the respondents were confronted with the question of ability to pay for the stated willingness to pay, most of them replied saying that they would like to have better lighting options and would pay from other informal sources of income. The Figure 16 below represents the average WTP of the households in the two income categories in the village. The subjective WTP was estimated as Rs. 95/month and Rs. 184/month for lower income and higher income household categories respectively. The estimates were in line with the earlier studies conducted in the other parts of the country having similar demographics as in this study. (James Cust, 2007) This method of measurement has once again reiterated the fact that, poor households end up paying a larger share of their monthly household income for the same amount of services availed.

It is a known fact that income is an influential character in choice of a household’s energy carrier. Here it is important to note that, the average monthly expenditure on energy or lighting needs is highest in the lowest income families. This exerts a tremendous pressure on the finances of the families and withholds them in seeking a better quality of life. It can be observed that in the lower income households the share of energy expenditure is close to 18% of the total household income. This is relatively a large share as the amount of earnings in the households are very less. This large share represents as full time struggle for survival – a type of existence largely unknown in the industrialized countries which drives them to make choices that hold them down the energy ladder. Therefore, small improvements in the energy basket of these families can have a dramatic impact on their living standards.

![Figure 17 Subjective measure of WTP in the village Penikalapadu for electricity services (Results from the survey data)](https://example.com/image.png)

Though ability to pay is the binding constraint for willingness to pay in the poor households, as stated earlier, WTP is also influenced by price and accessibility or availability of existing fuels for lighting and other services. Therefore, it is imperative to know the perceptions about the price and availability among the households in the village to know its influence on customers’ WTP. For this purpose, the survey tried to gauge peoples’ perception towards price of fuel for lighting in lower income households (un-electrified) and the price of electricity and kerosene combined together in higher income households (electrified). People
were asked to categorize their expenditure for fuel as very expensive, expensive, fair or cheap. Not surprisingly, none of the respondents have indicated their price of fuel as ‘cheap’ in both income categories. However, it was surprising that in the higher income category none of the respondents have indicated the expenditure as ‘expensive’.

From the survey data, though a clear linear relation of WTP with respect to price perception could not be established, it was observed that, willingness to pay a higher price increased with an increasing perception of lower price of existing fuel. This observation showed a slight distortion in the lower income household category where the respondents who perceive the price of fuel as ‘fair’ indicated a lower WTP than other respondents who think their fuel is ‘very expensive’ or ‘expensive’. The Figure 17 below represents the price perception of the two income categories in the village and Figure 18 shows the comparison of WTP based on price perception and among income categories. From the observed data it’s can be summarized that the perception of expenditure on energy has an influence on WTP for more or newer types of energy.

![Figure 18 Price perception of available energy in the village](image)

![Figure 19 comparing WTP based on price perception of available energy](image)
6 Potential impacts from polygeneration system

From the design of the polygeneration system, it is clear that the system delivers not only electricity but also other essential services like cooking gas and clean water. As stated earlier, it should be understood that the outputs from the polygeneration system for example, electricity is desired not for its own sake but for its use in other appliances. Therefore, a relationship between electricity and the appliances it powers and the services it generates out of those appliances needs to be understood in the context of this case study. The relationship between the outputs from the polygeneration system and the final services needs to be understood. The understanding of this relationship forms the basis for the assessment of impacts that polygeneration system could bring on the population in the village Penikalapadu. The following Figure 19 illustrates this relationship. Electricity, cooking gas, clean water and slurry are the primary outputs from the polygeneration system which foster the realization of various services through different intermediate appliances. The desire to own all or some of these appliance among the population in addition to the perceptions of safety etc. can help determine the potential impacts of the polygeneration system.

![Figure 20 Relation between Polygeneration system outputs and final services needed](image-url)
In the survey, villagers have expressed the desire to own essential appliances like the light bulbs, fans, TVs and radios. The provision of enhanced and efficient lighting for reading and space conditioning improves the time allocated for studying. Space lighting enhances indoor environment which helps in increased productivity in small income generation activities in the household. In addition to this the amount of money saved on account of switching to an efficient fuel (source of lighting) provides economic leverage to the household. Space lighting and use of other equipment like fans also improves the perception of comfort and security in and around the household which helps in leading a richer social life through greater community engagement. With access to television and radios, villagers will be better informed about the weather conditions to plan the crop sowing and harvest. Improvement in health awareness and behavioral patterns can be achieved through increased access to information through radio and television.

The water purifier in the polygeneration system, reduces the effort that men and women put in fetching clean water from the nearby streams and reduces their and their children’s vulnerability to water borne diseases. This improves their work days (number of days they fall sick reduces) thereby increasing the productivity consequently the total wellbeing of the household.

The use of efficient cooking fuel and technologies, primarily reduces the drudgery that the women go in collecting the firewood from the nearby forests. This improves the security of women by making them less vulnerable to assaults both from humans and animals. The time thus saved can be used in other productive activities which helps in generating additional income. The use of efficient fuels and technologies for cooking improves the indoor air quality thus having a direct impact on the health of women and children in the household. Additionally, the slurry produced from biogas generator in the polygeneration plant can be used as a fertilizer providing natural nourishment of the soil. This reduces the dependence on artificial fertilizers which are expensive in addition to their environmental effects.

6.1 Perception of benefits within the local population

Based on the prevailing local conditions where almost all households lack reliable access to electricity and other energy services, it is impossible to determine the benefits by observing households with and without electricity access. However, the desire for better services and perception of outcomes in relation to access to electricity and other energy services helps in the assessment of the conditions before and after the implementation of the project.

The contribution good health and education makes to one’s progress in society is undeniable. A healthy and well educated population in a village ultimately contributes towards nation building. Education equips one with knowledge and means to compete in the global market. Keeping in mind the importance of education in the growth of the individual, the villagers were asked about their perception towards education and the importance of electricity in helping improve educational outcomes. During the survey, people were asked about the role electricity could play in their children’s education. People were asked to rate their response on a four-point scale which indicate the levels of response as ‘strongly agree’, ‘agree’, ‘don’t know’ and disagree.

Initially, people were asked if ‘electricity is more important for their children’s education’. Most of the respondents do believe that electricity is important for their children’s education and will have positive effects on their performance. This has a subsequent good implication for their education. The figure below shows the survey responses and it can be observed that across the income groups and thereby electrification status groups, majority of people agree electricity has is an important issue concerning children’s education. As Figure 20 below shows, 93.5 % of all households either ‘strongly agree’ or ‘agree’ with the statement. Though majority of the higher income households strongly agreed (83.33 %) to the statement, majority of lower income household who have never had electricity before also agreed to the statement.
The villagers are aware of the fact that electricity makes better quality lighting possible as opposed to light from kerosene lamps. This is the reason why the above statement has received a great positive response.

The villagers were then asked if ‘electricity at night improves children’s reading time’. This is to assess if availability of electricity at night influences the time children spend on studying. Interestingly, only 50 % higher income households which have a partial access to electricity have strongly agreed to the statement and 33.33 % and 16.67 % have agreed and disagreed respectively. Where as in the lower income households 24 % and 56 % of them strongly agreed and agreed respectively and the rest 8 % disagreed that electricity at night improves children’s reading time. The Figure 21 below shows the survey results for this question.

Figure 21 Survey response to the statement “Having electricity is more important to children’s education”

![Figure 21](image1)

Figure 22 Survey response to the statement “electricity at night improves children's reading time”

To examine the influence of electricity on extra income generation opportunities, the villagers were asked if the unavailability of electricity causes any loss of livelihood. During the interviews it was observed that some of the villagers are engaged in informal income generation activates or expressed a desire to do so. During the survey, the results of which are presented in Figure 22, 67.7 % of people from the lower income...
households indicated that there is loss of livelihood for them due to the unavailability of electricity. Whereas 83% of higher income households have indicated that they are at a loss.

Figure 23 Perception of livelihood loss due to unavailability of electricity among the villagers

The unavailability of electricity restricts the women of the households to do the chores during daylight. To know the pattern and schedule of household chores the respondents were asked if they complete their household chores before dark. They were asked to respond to the statement ‘I finish my household chores before dark’. As shown in Figure 23 lower income households who have absolutely no access to electricity complete their chores before dark. Whereas the higher income households who have access to electricity also complete their chores before dark. This is due to unavailability of electricity even though they are connected.

Figure 24 Response to the statement "I finish my household chores before dark"

To discover how access to electricity helps in fulfilling the entertainment and information needs of the villagers, the survey contained questions asking if they would like to have a TV/radio and why do they like to have a TV or a radio. Not surprisingly, almost all of the households expressed a desire to have a TV after lighting. The main reason for having a TV was entertainment rather than a source of information even though some of them acknowledge that TV/Radio was a source of information. The villagers were asked to respond to the statement ‘TV is a source of entertainment to me and my family’. The Figure 24 below
indicates the responses of the villagers which can be termed as mixed. Even though the majority of the people perceive TV/radio to be a source of entertainment, the level of agreement is not very high in both income groups. It can be seen that 56% of low income households have agreed to the statement while only 16% have strongly agreed and a considerable 24% have disagreed. While in the higher income households the strong agreement is more than 33% and agreement is 50%.

Concerning safety in close proximity of their homes, villagers were asked if they feel safe to venture out in the evenings and night into the backyards of their homes. Though the villagers might feel safe in their homes, those with electricity will have a greater sense of security than those without. During the FGDs villagers have mentioned the menace of snakes and other rodents when they venture out in the evening. Keeping this in view the villagers were asked about their feeling for safety around their homes. They were asked to respond to the statement ‘I feel safe to venture out in my backyard in the dark’. As expected the 88% of the respondents don’t feel safe around their homes. The following Figure 25 illustrates the responses according to the income groups.
Based on the results gathered from the survey data and focus group discussions, the people in the village see an opportunity for a better life with improved energy access. They agree that, having reliable electricity is essential for their children’s education. This may not have the immediate impact as desired but can lead to higher streams of income over the individual’s lifetime. With electricity the quality of education also improves as the people in the house tend to use the available lighting to read more than what they are usually used to.

During the survey it was mentioned that many households depend on informal sources of income like making palates out of leaves and making ropes. With access to electricity, they will be able to spend more time thereby improving their productivity and consequently their income.
7 Conclusion

Polygeneration systems in which appropriate technology integration has been achieved can enhance the overall system efficiency and output without any significant technological breakthrough. This represents a decrease in the exploitation and consumption of natural resources resulting in reduced environmental burden and improved economic savings thus maximizing the impacts of cleaner and reliable energy access.

The findings of this report are a result of a minor field study and socioeconomic survey conducted in a rural village in India. Preliminary assessment during the field study showed that the chosen location lacked access to basic infrastructure like roads, reliable electricity grid connection and clean water services.

Based on the results of the survey and demand projection, the electricity demand for the village was calculated to be 36.6kWh/d with a peak load of 5.84kW and a clean water demand was estimated to be 2340 l/d. The cooking energy demand however was above the national average at 39.5kg/capita in a given month. Local resource assessment has revealed enough availability of solar energy and inadequate wind resource. Though the village has considerable amount of biomass resource in the form of cattle dung, calculations revealed a potential of 13961.25 m³/yr for the purpose of both electricity production and for the supply of cooking gas.

Keeping in mind the results from the demand and resource assessment, a combination of technologies which suit the local conditions and the important aspects of ease of maintenance & stability have been assessed. It was concluded that solar PV and biogas generator system are the most suitable technologies for this case and an optimum system configuration with the chosen technologies was designed using HOMER. This was necessary to verify the robustness of the system to cope with seasonal as well as unforeseen variations in the demand projections and existing resources. The final optimum system configuration consists of a 4.5kW biogas generator and 2kW solar PV system. This suffices the electricity and clean water needs of the whole village. Due to the limited biogas resource, initially only 60% of the households can be supplied with cooking gas and the rest can be supplied with efficient cooking technologies.

The results from the survey also showed that the villagers are willing to pay for the services although the price is considerably higher than what is offered by the utilities. This is due to the quality and reliability of the supply. They are quite aware of the uses and the positive effects electricity and cleaner environment can have on their quality of life. The data collected from the survey indicated that the villagers see a positive impact on the education of their children with increased reading time due to availability of light at home after school hours. Most of the respondents agreed that access to lighting at night improves children’s reading time. The data also revealed that due to lack of electricity and lighting, the villagers are at a loss of opportunity to generate additional income. With access to electricity thereby lighting, women will be able to perform household chores even after dark which enables them to work during the day. This increases their economic security in addition to the overall perception of physical security around the household which is absent in darkness.
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Appendix

Socio-economic survey questionnaire

1. Household Number
2. Name of the Respondent (Optional):
3. Total number of members in the household:
4. What is the education status of the family members?
5. What is the total average monthly income of the household?
6. What is your source of income? Primary and secondary if any?
7. How do you spend your income? Rank your preferences starting with 1 as the most important

<table>
<thead>
<tr>
<th>Items</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food/clothes</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td></td>
</tr>
<tr>
<td>Health care</td>
<td></td>
</tr>
<tr>
<td>Other specify</td>
<td></td>
</tr>
</tbody>
</table>

8. Do you own any livestock?

<table>
<thead>
<tr>
<th>Type</th>
<th>No. of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cow</td>
<td></td>
</tr>
<tr>
<td>Buffalo/Ox</td>
<td></td>
</tr>
<tr>
<td>Goat</td>
<td></td>
</tr>
<tr>
<td>Poultry</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td></td>
</tr>
</tbody>
</table>

9. Do you use the dung for any purpose?
10. What kind of fuel do you use for cooking in your house?
11. Is it easily available?  Mark (✓)
    ( ) Yes ( ) No
12. How much money or time do you spend to buy/collection cooking fuel?
13. If you use biomass, how much do you collect or buy?
14. What influences your choice of cooking fuel?

<table>
<thead>
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<th>Items</th>
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</thead>
<tbody>
<tr>
<td>Price</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td></td>
</tr>
<tr>
<td>Ease of use – type of stove</td>
<td></td>
</tr>
<tr>
<td>Health. Environment and safety</td>
<td></td>
</tr>
</tbody>
</table>

15. Do you have electricity in your home?
16. What fuel do you use for lighting and how much?
17. On an average how many hours of lighting do you need and what time of the day?

18. If you have access to electricity, what and how many appliances would you like to have?

<table>
<thead>
<tr>
<th>Type of appliances</th>
<th>Hours of usage</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Television/radio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water pump</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other _______</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

19. How is your current energy or electricity supply priced? What is your perception? (Fuel and/or electricity)?
   [1] Very expensive
   [2] Expensive
   [3] Fair

20. If there is no electricity supply or it is of bad quality, What are the consequences for you
   [3] Both

21. Are you willing to pay more for a better quality of energy and electricity?
   Yes (  ) No (  )

22. How much more are you willing to pay in addition to your existing expenditure?

23. How will you be able to pay based on your present economic situation?

24. What is the source of water (for drinking as well as other household purposes)?

25. How much water do you use in your household? Please, specify the daily requirement.

26. Do you have any problems with the quality and purity of water?
   Yes (  ) No (  )

27. Did you or your family members fall sick because of any of these illnesses or are sick now?

<table>
<thead>
<tr>
<th>Name of the diseases</th>
<th>Suffering households</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Man (number)</td>
</tr>
<tr>
<td>Diseases associated</td>
<td></td>
</tr>
<tr>
<td>Cooking/lighting</td>
<td></td>
</tr>
<tr>
<td>fuel(Asthma,</td>
<td></td>
</tr>
<tr>
<td>Tuberculosis, Eye</td>
<td></td>
</tr>
<tr>
<td>disease, Pneumoconiosis, Skin disease,</td>
<td></td>
</tr>
<tr>
<td>Acute Respiratory Infections,</td>
<td></td>
</tr>
<tr>
<td>Burn)</td>
<td></td>
</tr>
<tr>
<td>Diseases associated</td>
<td></td>
</tr>
<tr>
<td>Water(Skin disease,</td>
<td></td>
</tr>
<tr>
<td>Diarrhea, Numbness in the hands and feet,</td>
<td></td>
</tr>
<tr>
<td>black and weak teeth and nails)</td>
<td></td>
</tr>
</tbody>
</table>
28. If you have school going children, how many hours do they spend studying at home?

What is your response to the following statements?

29. ‘Having electricity at home specially at night is important for children’s education’
   Strongly agree [ ]
   Agree [ ]
   Don’t know [ ]
   Disagree [ ]

30. Electricity at night improves children’s reading time.
   Strongly agree [ ]
   Agree [ ]
   Don’t know [ ]
   Disagree [ ]

31. There is loss of income generation opportunities and/or livelihood due to lack of reliable electricity.
   Strongly agree [ ]
   Agree [ ]
   Don’t know [ ]
   Disagree [ ]

32. I finish my household chores before dark due to lack of proper lighting
   Strongly agree [ ]
   Agree [ ]
   Don’t know [ ]
   Disagree [ ]

33. TV/radio is a source of entertainment for our family
   Strongly agree [ ]
   Agree [ ]
   Don’t know [ ]
   Disagree [ ]

34. I feel safe to venture out in my backyard in the dark
   Strongly agree [ ]
   Agree [ ]
   Don’t know [ ]
   Disagree [ ]